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CAVITATION.

BY HENRY F. SCHMIDT, MEMBER.

In the February, 1928, issue of the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, there was published an article by the writer on some Screw Propeller experiments, with particular reference to pumps and blowers.

In this article, the writer's theory of the action of propellers was presented, which is that the flow into a propeller is similar to that through a sharp-edged orifice, there being a contraction of the stream and an increase in velocity within the axial length of the propeller, the velocity at the trailing edge being 1.6 times the velocity at the entrance edge, or $\frac{1}{0.625}$, .625 being the coefficient of the vena contracta. It did not occur to the writer at that time

that the same relationship may be employed for determining the cavitating speeds of propeller type pumps. Another crude way of expressing the preceding theory is that the propeller blades simply serve to produce holes into which the water or air can flow, and it is obvious that the maximum velocity which the water can acquire in flowing into this hole is that corresponding to the total head on the water. In the case of a pump taking its suction from an open channel, the total head available will be atmospheric pressure, or approximately 34 feet of water plus the actual submergence in feet of the propeller below the surface of the water.

By the writer's theory, this can only strictly apply to propellers having a projected area ratio of 62.5 per cent, and a ratio of pitch ratios of leading to trailing edge of 1.6 or $\frac{1}{0.625}$.

A formula for the cavitating speed of propeller pumps can be deduced as follows:

If pr is the pitch ratio of the inlet edge, D is the diameter of the propeller in inches and N = rpm; then, at normal capacity, that is, when the water is entering the blade tangentially at its inlet edge, the velocity of the water entering the propeller will be

$$\frac{D}{12} \text{ pr } \frac{N}{60} \text{ feet per second}$$

Now, assuming the above-mentioned contraction theory, the velocity at the exit of the propeller and that required in order that the water may remain in contact with the back of the blade will be

$$\frac{\frac{D}{12} \text{ pr } \frac{N}{60}}{0.625}$$

and this velocity must be less than that corresponding to the total head available at the inlet, i.e., 32 plus the submergence in feet (using 32 in place of 34 to allow for the vapor tension at the average water temperature).

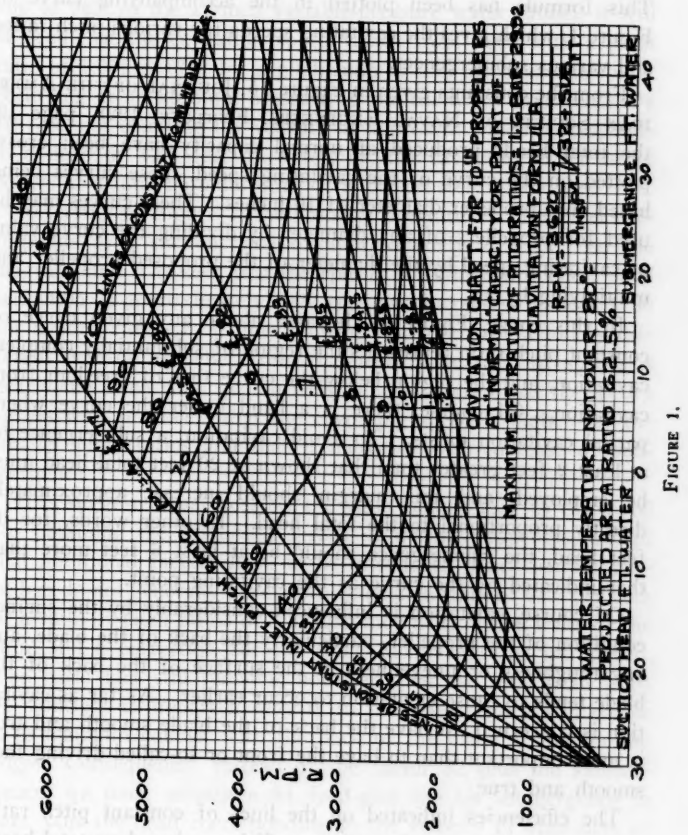


FIGURE 1.

Hence

$$\frac{\left(\frac{D}{12}\ pr\ \frac{N}{60}\right)^2}{\frac{0.625}{2\ g}} = 32 + sub$$

Whence

$$N = \frac{3611.25}{D\ pr}\ \sqrt{32 + sub}$$

This formula has been plotted in the accompanying curve of Figure 1, which gives the cavitating speeds for various pitch ratios and various submergences.

From the constants given in Figure 15, JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, February, 1928, page 19, the total heads produced at normal capacity have been cross-plotted on the curve of the cavitating speed, these curves being based on a propeller diameter of 10 inches. These curves may be used for propellers of any diameter by dividing the curve value of cavitating speed by the diameter of the proposed propeller and multiplying by 10.

In this curve, Figure 1, the area above any given curve of constant pitch ratio represents the region of substantially complete cavitation, and the region below the curve that of freedom from cavitation. Of course, there is a band under the curve where partial cavitation exists. To avoid cavitation, a submergence of at least 2 feet greater than that shown at 20 feet total head must be employed, and this margin should increase approximately directly proportional to the total head. In other words, for 60 feet head, the submergence should be at least 6 feet more than that indicated by the curve as the cavitating point.

Of course, cavitation is influenced considerably by the surface condition of the propeller, particularly the back of the blade, and any roughness or unevenness in the surface of the back of the blade tends to cause cavitation to occur earlier. As far as cavitation is concerned, to have the back of the blade smooth and true is more important than to have the front or so-called driving face smooth and true.

The efficiencies indicated on the lines of constant pitch ratio are those at the point of maximum efficiency, based on total head, of the propeller operating in the pump at normal capacity and in the region free from cavitation.

The writer's theory has been very severely criticised, and there is probably no one who agrees with him. However, referring to the paper, "Tests of Model Propellers of Various Blade Sections," by Rear Admiral D. W. Taylor (CC) U. S. N., published in the Transactions of Naval Architects and Marine Engineers, Vol. 38, 1930, plate 106, showing results of tests, group E models, numbers

960 to 963, in the 12-inch variable-pressure water tunnel, it will be seen that the cavitation speed varies from 1200 with a pitch ratio of 1.05, to 1840 for a pitch ratio of .60, the cavitating point occurring at an absolute pressure in the tunnel of approximately 10 feet, not counting the velocity of approach, which corresponds to a head of 1.65 feet of water, or, the cavitating point really occurs at a total absolute head of approximately 11.65 feet.

Referring to Figure 1, the absolute pressure of 11.65 feet corresponds to a suction head of approximately 22.4 feet on the diagram, and it is seen that the rpm of a 10-inch propeller, pitch ratio 1.05, is approximately 1000 rpm, and increases to about 1780 for a pitch ratio of .6, thus showing that even for a totally different type of propeller from that tested, the ratio of speeds is nearly the same, and, qualitatively at least, shows that the theory agrees with practice,—that the cavitating speed is higher for the smaller pitch ratios and that it increases with increase of submergence.

It is suggested that possibly the same method may be employed for obtaining the cavitating speeds of marine propellers, except that additional factors have to be introduced, since marine propellers do not generally have a projected area ratio of 62.5 per cent or a ratio of pitch ratios of 1.6; also they work in the wake of the ship, and a correction for the wake factor must be introduced. The basic fact still remains, however, that the total head must be sufficient to impart a velocity to the water which will enable it to maintain contact with the back of the blade at the trailing edge. Consequently, instead of the factor 32 plus the submergence, we must substitute 34 feet plus the tip submergence in feet, plus the head corresponding to the velocity of approach, or

$$\frac{[v\,(1 - w)]^2}{2g}$$

in which w is the wake factor and v is the velocity of the ship in feet per second.

Referring to the writer's article in the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS of February, 1928: An examination of the curves in Figures 18, 19 and 20, indicates that the head or thrust produced by the propeller at constant speed

varies with the projected area ratio, increasing up to a projected area ratio of unity for pumps with guide blades. It is also seen by reference to Figures 21, 22, 23, and 24, that the head or thrust at constant speed increases with the ratio of pitch ratios, the projected area ratio remaining constant. As the revolutions required to produce a given thrust are greater for a small than a large projected area ratio, our formula for cavitation will be

$$\frac{D}{12} \times \frac{N}{60} \frac{pr\ rpr}{k} = \sqrt{2g\left\{34 + Sub + \frac{[v\ (1 - w)]^2}{2g}\right\}}$$

in which rpr is the ratio of the pitch ratios of leading to trailing edge, and k is a factor varying from zero to unity within an increase of projected area ratio from zero to 100 per cent, as determined on a percentage basis from the increase of head produced by propellers of various projected area ratios, Figures 18, 19 and 20 of the writer's article previously referred to. This relationship is shown in the curve, Figure 2. Solving the equation

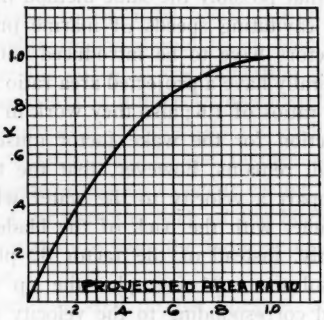


FIGURE 2.

previously given for N, we get

$$N = \frac{5800\ k}{Dpr\ rpr} \times \sqrt{34 + Sub\ \frac{[v\ (1 - w)]^2}{2g}}$$

which would be the cavitating speed.

It should be noted that for a very thin-bladed, true screw, rpr = 1, whereas for a very thick blade, it may be over 2, espe-

cially at the root. The average rpr for actual screws is probably never less than about 1.25.

In regard to the wake factor, this should be corrected for the true velocity of approach or advance of the propeller through the water in which it is working. Whereas the wake is positive in the case of a single-screw vessel at low speed, the writer believes that this is not true of fine-line vessels, with twin or quadruple screws having speed length ratios

$$\frac{V}{\sqrt{L}} > 1.0$$

in which case the wake factor is negative in the region where the propellers are working. This must be so for speed length ratios in excess of 1.0, since, under this condition, there is a trough or partial trough, at the stern, indicating a pressure lower than that of the surrounding undisturbed water, and a velocity relative to the ship greater than that of the ship through still water.

In order to apply the formula for determining the cavitating point of ships' propellers, it is necessary to find the effective pitches of the leading and trailing edges since the effective pitch of the leading edge is required in the formula as well as the ratio of pitch ratios, for which the mean value at about .7 radius is used.

Figure 3, which is not drawn to scale, shows two of the blade sections tested by Admiral Taylor in the pressure tunnel, and on these are drawn dotted lines approximately bisecting the contour lines of the leading and trailing edges. In each case the angle which the dotted bisector makes with the nominal face pitch line is added to or subtracted from, as may be appropriate, the nominal pitch angle, to give the effective pitch angle. The tangent of this effective pitch angle multiplied by π and by the radius at which it is taken expressed as a decimal of the tip radius is the effective pitch ratio.

The following tables illustrate the method of using the formula and show the comparison of the results obtained by this method with those given by Admiral Taylor in his paper previously referred to.

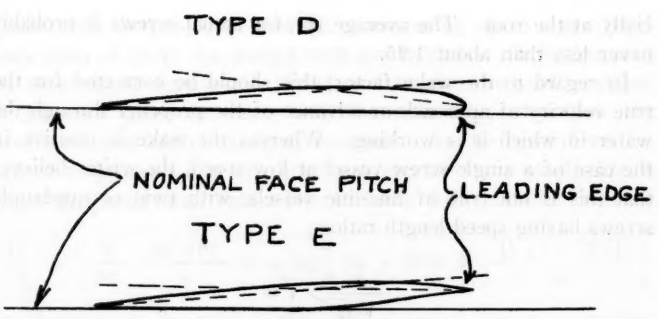


FIGURE 3.

In the case of type E propellers it will be noted that the effective pitch of the leading edge is the same as the nominal pitch, the reason for which is readily seen from Figure 3.

PROPELLER DATA FROM ADMIRAL TAYLOR'S PAPER
TYPE D 8 INCH DIAMETER AIRFOIL SECTION
TAKEN AT .67 RADIUS.

Face Pitch Ratio	.6	.75	.9	1.05
Projected Area Ratio	.473	.456	.438	.42
K from Figure 2	.72	.70	.69	.68
Ratio of Pitch Ratios	2.23	1.88	1.77	1.67
Effective Pitch Ratio Leading Edge	.395	.55	.65	.78
Absolute Cavitating Head	12	8.8	7.7	7.0
Absolute Total Cavitating Head	13.6	10.4	9.3	8.6

Velocity of advance 6 K = 1.60 Foot Head

$\frac{PA}{DA}$	*Calculated*	*Test*
.6 — RPM $= \frac{5800 \times .72}{8 \times .395 \times 2.23}\sqrt{13.6}$	= 2190	2060
.75 — RPM $= \frac{5800 \times .70}{8 \times .55 \times 1.88}\sqrt{10.4}$	= 1585	1560
.9 — RPM $= \frac{5800 \times .69}{8 \times .65 \times 1.77}\sqrt{9.3}$	= 1325	1360
1.05 — RPM $= \frac{5800 \times .68}{8 \times .78 \times 1.67}\sqrt{8.6}$	= 1105	1116

Propeller Data from Admiral Taylor's Paper

Type E 8 Inch Diameter Distorted Airfoil Section Taken at .7 Radius.

Face Pitch Ratio	.6	.75	.9	1.05
Projected Area Ratio	.473	.456	.438	.421
K from Figure 2	.72	.70	.69	.68
Ratio of Pitch Ratios	1.58	1.37	1.33	1.32
Effective Pitch Ratio Leading Edge	.6	.75	.9	1.05
Absolute Cavitating Head Ft.	9.8	9.8	9.8	9.8
Absolute Total Cavitating Head Ft.	11.4	11.4	11.4	11.4

Velocity of advance 6 K = 1.6 Foot Head.

$\frac{PA}{DA}$		*Calculated*	*Test*
.6	$\text{RPM} = \frac{5800 \times .72}{8 \times .6 \times 1.58}\sqrt{11.4} =$	1850	1840
.75	$\text{RPM} = \frac{5800 \times .70}{8 \times .75 \times 1.37}\sqrt{11.4} =$	1670	1460
.9	$\text{RPM} = \frac{5800 \times .69}{8 \times .9 \times 1.33}\sqrt{11.4} =$	1390	1290
1.05	$\text{RPM} = \frac{5800 \times .68}{8 \times 1.05 \times 1.32}\sqrt{11.4} =$	1190	1200

It may be pointed out that the formula for the cavitating speed of marine propellers shows that—

1. The revolutions and thrust per square inch increase with the increase of ship's speed.
2. The revolutions increase with increase of projected area ratio.
3. Thin blades have a higher cavitating speed than thick blades.
4. The total head or equivalent submergence at which cavitation occurs varies as tip speed squared.
5. Small pitch ratios give higher cavitating speeds.
6. That the cavitating point is not affected by blade shape except as the shape affects the effective pitch and ratio of pitch ratios.

All of these are in general agreement with past experience.

For general use, the cavitation formula is more convenient in the form

$$\text{Rpm} = \frac{483\ k}{\text{Dpr}\ \text{rpr}} \sqrt{34 + \text{Sub} + \frac{[v\ (1 - w)]^2}{22.5}}$$

in which D is in feet and V is in knots. For convenience, the value of pr $\times$ rpr has been plotted in Figure 4 for blade thickness ratio, .05, and various blade width ratios shown in Figure 5.

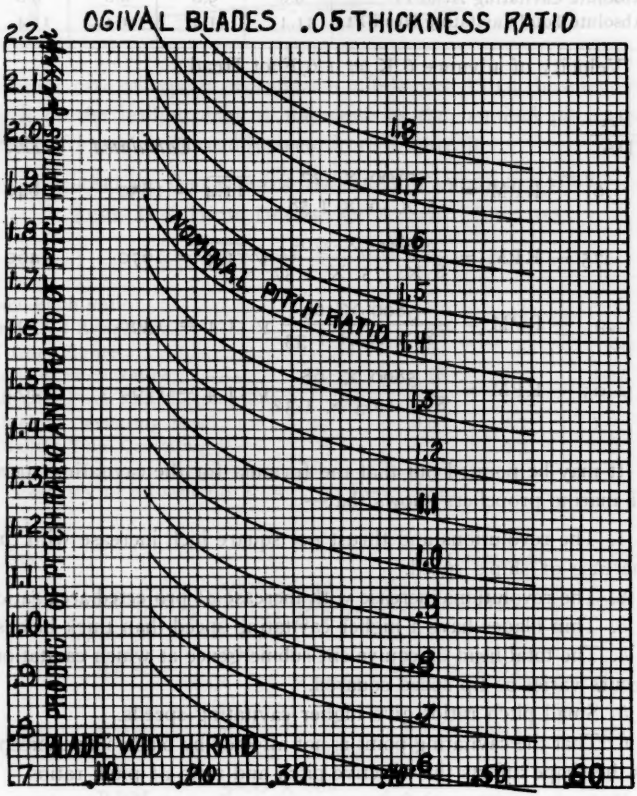


FIGURE 4.

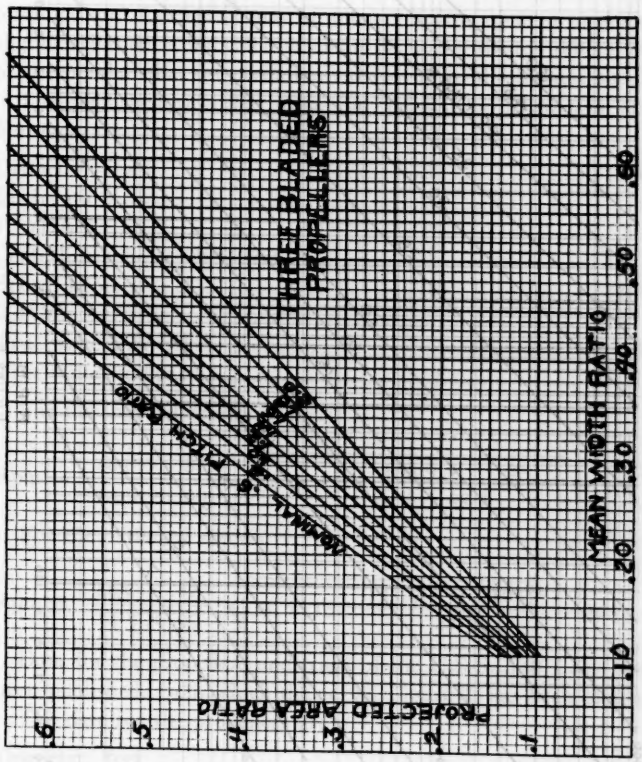

THREE BLADED
PROPELLERS
MEAN WIDTH RATIO
10
20
30
40
50
60
PROJECTED AREA RATIO
.1
.2
.3
.4
.5
.6
NORMAL
PITCH RATIO

FIGURE 5.

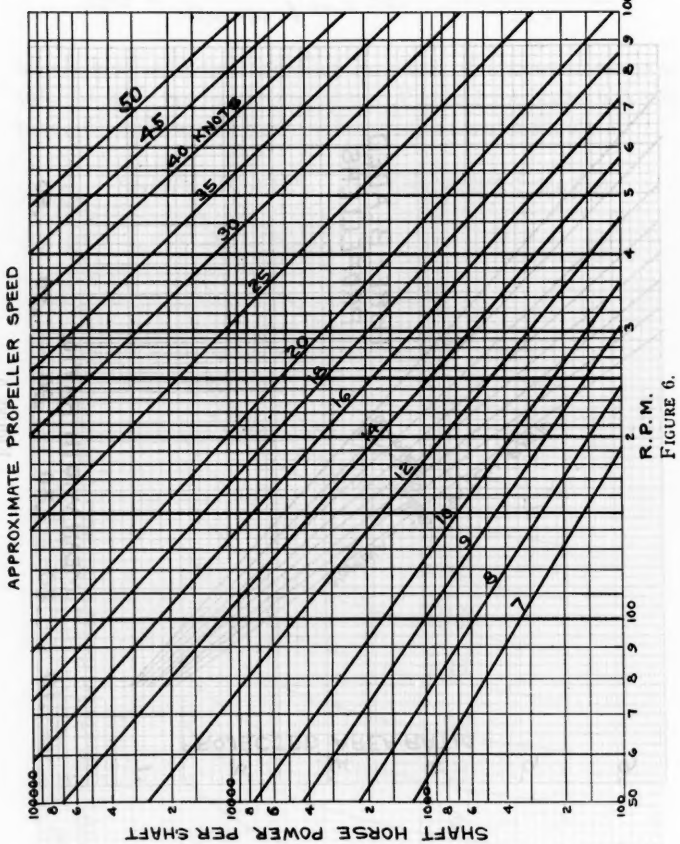

APPROXIMATE PROPELLER SPEED
50
45
40 KNOTS
35
30
25
20
18
16
14
12
10
9
8
7
SHAFT HORSE POWER PER SHAFT
10000
8
6
4
2
100
50
R.P.M.
1000

FIGURE 6.

A curve showing the approximate propeller revolutions which give the best combination of reasonable propeller efficiency, size, weight, and cost of propelling machinery for vessels of different speeds, is shown in Figure 6.

As a check of the formula, the performance of the U.S.S. *Saratoga* and *Lexington* may be taken. In the opinion of some, slight cavitation is indicated at about 33 knots, though others are of the opinion that no cavitation existed up to the highest speed.

The published propeller data for the U.S.S. *Lexington* and *Saratoga* are:

Diameter, feet	14.9
Pitch ratio	.89
PA/DA	.63
Centerline submergence, feet	15
Speed, knots	33.9
R.P.M.	319
True wake, inboard	—.05
True wake, outboard	—.10

For the inboard screws

$$\text{Rpm} = \frac{483 \times .88}{14.9 \times .99} \sqrt{34 + 15 + \frac{[33.9(1 + .05)]^2}{22.5}} = 294$$

For the outboard screws

$$\text{Rpm} = \frac{483 \times .88}{14.9 \times .99} \sqrt{34 + 15 + \frac{[33.9(1 + .10)]^2}{22.5}} = 303$$

Data for the propellers and trials of the U.S.S. *Salt Lake* have been published, from which the curve, Figure 7, has been plotted.

The data for the propellers are:

Diameter, feet	12
Pitch	11.75
Pitch ratio	.985
PA/DA	.55
Width ratio	.432
K, from Figure 2	.805
pr × rpr	1.12

Substituting various values for the speed, V, in the formula, the curve of cavitating rpm was obtained, as shown in Figure 7. The intersection of the curve of cavitating rpm with the trial rpm is the point at which cavitation begins. This is clearly indicated by the sudden increase of revolutions beyond this point. The portion of the cavitating curve to the left of the intersection repre-

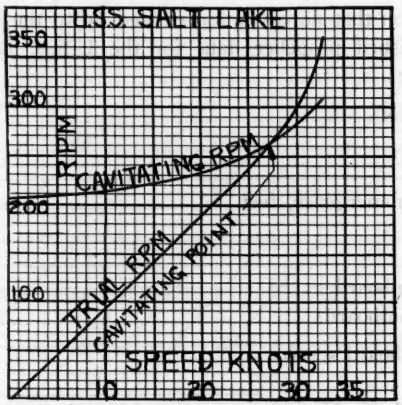


FIGURE 7.

sents the revolutions at which cavitation would begin either in starting the ship from rest or when towing with various resistances, which would give the various ship speeds. The portion of the cavitating curve to the right of the intersection merely indicates that the propeller is inadequate to drive the ship without cavitation.

What happens beyond the cavitating point may be seen by comparing the action of a normal propeller with one which is in cavitation.

The following calculation shows what happens after the cavitating speed is exceeded, and explains the portion of the cavitating curve to the right of the speed–rpm curve.

For a normal propeller, we may write for the thrust developed

$$T \propto \underbrace{\left(\frac{A \times P \times Rps \times \rho}{g}\right)}_{\text{mass}} \underbrace{\Big(P \times Rps - V\,(1 - w)\Big)}_{\text{acceleration}} \text{ or } T \propto Rps^2$$

$$T \propto V^2 \text{ or } Rps \propto V$$

Where A = Area of flow through propeller
ρ = Weight, cubic feet water
P = Pitch feet
V = Speed of ship, feet per second

Now, if the propeller is too small for the ship, or the rps are increased, a point is reached where the water can no longer keep in contact with the blades and we have cavitation; then the question for thrust takes the form

$$T \propto \underbrace{\left(\frac{PA\sqrt{2g\left[34 + Sub + \frac{[v(1-w)]^2}{2g}\right]}}{g}\right)}_{\text{mass}} \times \underbrace{\left(P \times Rps - \sqrt{2g\left[34 + Sub + \frac{[v(1-w)]^2}{2g}\right]}\right)}_{\text{acceleration}}$$

the term $\sqrt{2g\left[34 + Sub + \frac{[v(1-w)]^2}{2g}\right]}$

being the limiting velocity of feed to the propeller and limits the mass upon which it can act.

$$\text{Now } T \propto Rps$$
$$\text{But } T \propto V^2$$
$$\text{therefore Rps. } \propto V^2 \text{ or greater}$$

which accounts for the sudden increase in Rpm when the cavitating speed is reached. When the cavitating speed is reached, there is a perfect vacuum back of the blades and the additional thrust beyond the point is due to the face of the blade pushing the water flowing into it due to the vacuum back of the blade, since the P $\times$ Rps exceeds the possible rate of flow into the vacuum. This, however, causes a very rapid increase in the rotation imparted to the wake with a reduction of the axial component, which becomes increasingly less than

$$P \times Rps - \sqrt{2g\left[34 + Sub + \frac{[v(1-w)]^2}{2g}\right]}$$

so that to produce the necessary thrust, Rps $\propto > V^2$.

In applying the cavitating formula to new designs, the procedure is as follows:

The formula may be written in the form

$$D = \frac{483\ K}{Rpm \times pr \times rpr} \sqrt{34 + Sub + \frac{[v\ (1 - w)]^2}{22.5}}$$

in which D and pr × rpr are the unknown.

As an example, let us assume that we wish to design a propeller for a destroyer having a speed of 42 knots, two-shaft arrangement, 40,000 H.P. per shaft. At this speed, it is safe to assume that the wake factor would be at least minus 10 per cent. From Figure 6 for 42 knots and 40,000 H.P. per shaft, a propeller speed of about 475 R.P.M. would be suitable. Because of the high power and speed, we know that the projected area ratio will have to be large, and if we assume .70 from Figure 2, K = .91. So, we have

$$D = \frac{483 \times .91}{475 \times pr \times rpr} \sqrt{34 + 11 + \frac{[42\ (1.10)]^2}{22.5}} = \frac{11.0}{pr \times rpr}$$

Assuming nominal pitch ratios of .8, .9, etc., we obtain:

Pr.	pr × rpr	D	P.	P + D
.9	1.005	10.95	9.85	20.80
.95	1.05	10.45	9.93	20.38
1	1.105	9.95	9.95	19.90
1.1	1.205	9.13	10.05	19.18
1.2	1.3	8.45	10.15	18.60

The desirable diameter and pitch to be selected will be within this range, it now being necessary to make the calculation for H.P. and diameter in the usual manner.

The formula given is necessarily tentative since the projected area ratio factor, K, is derived from propeller blowers where the propeller is working in a closed channel in combination with guide vanes, so that necessarily the factor K would be considerably different than for a propeller operating in the open, but the writer was compelled to use these data, as no other are available for actual ships' propellers showing the variation of this factor with projected area ratio. It is, in fact, very surprising that the formula with the factor K so derived seems to check marine propellers as well as it does.

As for the general form of the formula, as far as the writer knows, it is the only one in which the effect of atmospheric pressure, submergence, and ship's speed are taken into account. It is interesting to note Mr. Normand's formula, which is given in the form

$$ND^2\gamma^{\frac{3}{4}} = C\,\frac{P}{V^2}$$

in which N = number of screws
D = diameter

$$\gamma = \frac{\text{developed area}}{\text{disc area}}$$

P = maximum H.P.
v = corresponding speed of ship in knots
C = a factor which should not be less than .6 but can with advantage exceed .8.

If we substitute for the H.P. its equivalent thrust × pitch × rpm × a constant, and substitute for P its equivalent D × pr, we can solve for rpm and obtain

$$\text{Rpm} = \frac{C_1\left(\frac{\text{Dev A}}{\text{DA}}\right)^{\frac{1}{4}} V^{\frac{2}{3}}}{\text{D pr}}$$

which is somewhat of the same form as the writer's formula, but it is noted that whereas Barnaby's rule includes only pressure per square inch of projected area, Normand's formula also takes into consideration the ship's speed, which, however, only enters as the ⅔ power and the area factor as the ¼ power, whereas in Barnaby, the area factor enters directly. It therefore appears that neither Barnaby's formula nor Normand's is theoretically of the correct form.

The writer wishes to state that this is presented, not with any thought that it is a solution of the cavitation problem as it relates to marine propellers, but merely with the hope that it may provide a new line of thought, or possibly, by the substitution of new constants from actual cavitation experiments, it may be developed into a useful guide.

A SHORT HISTORY OF THE NAVAL USE OF FUEL OIL.

PART I.*

BY LIEUTENANT JAMES E. HAMILTON, U. S. N., MEMBER.

In 1819 the Steamship *Savannah* crossed the Atlantic inaugurating the service of steam propelled vessels for this purpose. Sixty-one years later, in 1880, the list of vessels of war of the United States, carried a total of 113 names. Ninety-one of these were either screw or paddle driven and 22 were sail propelled. With one exception, the sailing vessels were out of commission or in use as store, station, or training ships. The day of sail had passed for the Navy of the United States.

Up to the beginning of the war with Spain, the engineering effort of the Navy was at first expended in the most part for designing and building the "New Navy." Coal had been and was the only practicable fuel for use on ships which developed any amount of power or were at all removed from a bunkering source. During the years preceding the war the use of coal under boilers and the methods of handling it were developed to a high state for the day and age. The development attained is clearly shown by the famous cruise of the *Oregon* from the Pacific to join the Atlantic fleet.

INTRODUCTION.

With the close of hostilities in 1898, Naval officers were freed from the problems of war and were in a position to devote their energies to the technical problems upon the solution of which, advancements of Naval technique depend.

Steam was accepted without question but with all of its outstanding advantages over the older forms of motive power, it had its limitations. Some of these were:

a. The necessity for large, heavy equipment installations for generating the steam.

* This is the first article of a series, others of which will appear in subsequent issues.

b. The necessity for alloting large volumes of valuable space in each ship for the storage of fuel.

c. The requirement of a large complement of men solely for handling the fuel and for feeding it to the boilers.

d. The dependence upon an outside source for replenishment of fuel at too frequent intervals.

e. The need for disabling the ship for several hours each time that fuel had to be taken on board.

f. The fact that coal fires and coal fired boilers became dirty after a few hours steaming at high speeds with a consequent reduction in the ship's maximum speed.

g. The physical hardship on the crew of maintaining high speeds for protracted periods.

Any technological change which would ameliorate or eliminate any of the disadvantages of the coal fired steam plant would tend toward an overall increase of military efficiency of the fleet and of each individual ship.

The steam turbine was on the horizon as a replacement for reciprocating engines. It offered tremendous advantages but none which would improve the generation of steam. The internal combustion engine, which even today is just starting on its climb to full utilization, was not even worthy of consideration for the development of so much power with so little weight of equipment as men-of-war required.

All of the disadvantages listed above were inherent in the fuel—coal. There was one possible substitute for coal. Petroleum had been in successful use both ashore and afloat in the Caspian Sea and on the Volga River in Russia for a number of years; but then the use there was not military and the source of supply was immediately close. It was logistically just like burning wood on Mississippi River steamboats. In California, oil was burned in most shore plants and in an increasing number of coastwise ships. Both Russia and California had large reserves of petroleum while coal had to be transported from distant mines and was therefore very expensive.

The engineers of the Navy had followed the use of liquid fuel with deep interest. The possibilities offered by its substitution for coal were enormous. But, was its use feasible for Naval

vessels? Coal was well known. Its disadvantages were recognized and none of them had been insurmountable. Coal was subject to spontaneous combustion in storage and generated explosive vapors which had to be guarded against but petroleum was a liquid which contained explosive gases and was itself inflammable. What would happen to it if stored close to hot firerooms, if it leaked from some part of the system, or if a tank containing it was pierced by a shell in battle?

Handling and burning equipment was available for using coal and it could be handled quite efficiently if enough trained men were provided. Would the equipment which permitted fuel oil to be used on a locomotive, or a merchant ship, or a stationary boiler, be adaptable to a naval vessel with its space limitations and variable steam demand?

Coal could be either good or bad for steaming purposes but good coal could be located in a mine and no coal need be purchased for the Navy except that which came from a known source. What was known about the characteristics of petroleum as a boiler fuel and with its intermediate step of refining would the quality of the supply be assured.

A coal seam could be explored and the amount of good minable coal could be determined with very close accuracy. It was known that the country held sufficient coal to satisfy the demand for many generations. Petroleum was a mineral of a different kind. If the indications were promising, a well would be drilled. Oil might be discovered by this well or it might not. If it was found an estimate could be made of the amount which could be obtained from that field only after several months or even years and this estimate was not very accurate. Could the quantity of the fuel oil supply be assured?

With all of the uncertainties which existed, extreme caution was necessary before anyone could take the responsibility for committing the Navy to the use of fuel oil in place of coal. The steps leading up to the change from coal to oil and the subsequent events of importance present a very interesting history. It is the intention of this paper to describe the important events in connection with the use of fuel oil in naval vessels.

The history of fuel oil or liquid fuel for naval use might be divided into chronological periods, each such period ending and the next beginning with some critical event. This method is perhaps permissible up to about 1910 when the entire question can be considered to have been quite general. At that point the question became a much more definite *problem* with a number of subdivisions each having its own problems.

The chronological division which will be used and the names assigned to each period are as follows:

I. Prior to 1902—Dabbling.
II. 1902 to 1904—The Navy Liquid Fuel Board.
III. 1904 to 1910—Early Application.
IV. 1910 to 1916—The Rise of Oil.
V. 1917 to 1919—The War Period.
VI. 1919 to 1933—The Post-War Period.
VII. 1933 and after—The Future.

The first three periods will be considered under only one general head. Thereafter, the subject must be subdivided into the following headings:

1. *Utilization*—This subject covers the mechanical features of handling and burning fuel oil. It is strictly an engineering subject. The details are beyond the scope of this paper and the subject will be generally described only.

2 *Quality*—This subject has to do with the characteristics of the oil and the specifications covering its purchase. It will also be described only in a general way.

3. *Application*—This subject covers the general methods by which the use of fuel oil has been and is applied to vessels of various types.

4 *Source*—This subject covers the natural resources of petroleum and possible substitute or replacement materials; their location, control, and naval value.

5 *Supply*—This subject covers the events which intervene between the removal of the petroleum from its source and its acquisition by the Navy.

6 *Distribution*—This subject covers the events which intervene between the acquisition of the fuel oil by the Navy and its bunkering on board naval vessels.

I. PRIOR TO 1902—DABBLING.

It has been stated that long before the end of the nineteenth century, fuel oil was widely used in California and Russia. It was highly satisfactory for use in shore plants. In shipboard installations it was practicable only where an adequate supply of fresh water was available. The only method in general use at that time for atomizing the oil was by steam. The consumption of water was too high for ships which could not fill their fresh water tanks quite frequently. Its marine use was therefore naturally restricted to ferry boats, tugs, and coastwise steamers.

The JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS in 1890 described the first oil-burning man-of-war, the torpedo boat *Sunderland* built in England. This vessel was fully described in "Engineering" for January 10, 1890 with a complete account of her trials. It was stated that the use of fuel oil was highly successful. No further information can be found concerning the *Sunderland*. Her name does not appear on any Navy list for the last decade of the nineteenth century. If she was ever commissioned for naval use it must have been under another name or her career was a very short one. It seems probable that the early glowing accounts were not well founded and that the vessel was left on the builder's hands for disposal. The information available does not show that she was built to an Admiralty order. This is substantiated by the fact that, in 1898, the *Surly* was reported as the *first* British oil-fuel-burning torpedo boat.

A year later, in 1891, the JOURNAL commented on certain experiments being conducted by the Italian Navy. It appears from the records that Italy took the initiative in experimentation and then in application of fuel oil to naval use. However, the first application was entirely different from the one which has developed.

Italy fitted steam atomizers to the boiler of one torpedo boat and used oil in conjunction with coal. It was not believed that a man-of-war could depend on oil alone but there was little doubt that oil

could be used to maintain the output of a coal fired boiler after its efficiency dropped off due to dirty fires. The oil was sprayed onto the bed of incandescent coal on the grate and added its heat of combustion to that of the coal. Apparently the Italians were satisfied with the results of the first installation for in 1895 they had eight torpedo boats similarly fitted.

In 1894 a merchant steamer, the *Baku Standard,* made the round trip between England and the United States using oil alone. This was the first recorded *ocean* voyage with entire dependance on oil as a fuel. The ship had a large evaporating plant, fortunately. Her expenditure of water for steam atomization was greater than that of oil. One fact concerning the voyage should be enlightening to our modern engineers. The *Baku Standard* left England with three hands in the fireroom force. On the first day out, one of these was disabled and the remaining two operated the boiler plant for the rest of the crossing.

In 1894 and 1895 a number of lectures on engineering subjects were given to the class at the Naval War College. One of these, delivered in August, 1895 by Passed Assistant Engineer John R. Edwards, U. S. N., covered the entire field of liquid fuel as of that date. In his paper, Edwards sketched the history of the commercial and naval experiments with and adoption of liquid fuel. He scouted the extravagant claims of many proponents of liquid fuel and listed the difficulties which would have to be overcome before coal could be displaced. The disadvantages which he listed are of enough interest to warrant quoting them in full:

"DISADVANTAGES AS A FUEL.

"The disadvantages are:

"1st. The erection of oil tanks and supply pipes in the place of existing coal stations, so as to insure the rapidity of taking oil on board alluded to above.

"2nd. The loud noise occasioned by sprinklers, which is exceedingly inconvenient in the case of passenger steamers. It would be downright fatal for torpedo boats.

"3rd. The combustibility of oil, which might occasion an explosion in the event of a shell hitting the tanks.

"4th. The very small number of oils which can be used as a fuel. If estimated at a maximum, the annual output of all the natural oil of the world amounts to about six million of tons of mineral oil, three-quarters of a million tons of tar oil, and a quarter of a million tons of slate or shale oil, altogether seven million tons. Modern industry which transforms these into liquid fuel, lubrication oils, benzole, paraffin, etc., cannot spare them; at most it can leave us about 20 per cent of the original weight in residuals, which, however, would only represent a fifth part of the fuel required annually by the steam navigation of the world. On the other hand, the latter absorbs about a thirty-third of the annual output of four hundred millions of tons of coal of the world, or twelve million tons.

"5th. The enormous cost of liquid fuel at present is, however, the rock on which all attempts at introducing its use more widely in merchant vessels must founder. According to the present prices of coal and oil residuals, the latter, notwithstanding their higher power of evaporation, are about three times as dear as coal. The price of oil will always be unstable.

"6th. Difficulty in overcoming the objectionable odor. This objection was one of the reasons why the Southern Pacific Railway abandoned the use of petroleum fuel in the furnaces of their ferry boats.

The impossibility of overcoming the formation of gas and the consequent odor, and also the difficulty of examination of compartments in which this material has been carried, will retard somewhat its adoption on board ship, even if the other difficulties were removed.

"7th. Destructive action upon the plates and rivets. One of the officials of the Standard Oil Company says: 'We have four ships running out of New York carrying petroleum to foreign countries, and about every two years it is necessary to cut out and renew a large number of rivets sometimes reaching up into the thousands, in order to overcome the deteriorating effect incident to the penetration of oils along the seams. It will affect water bottoms in the same way and to fully as great an extent. There is a great difference between the carrying of refined oil or the raw product. In the latter, the generation of gas is the maximum, in the refined it is

the minimum. A few years since, the Standard Oil Company, of New York, built a steam vessel for the carrying of refined oil, and she was reasonably successful and satisfactory. Later they attempted to carry crude petroleum in her, and within three months thereafter they had a very disastrous explosion on board, practically wrecking the vessel.'

"8th. Exceeding and intelligent care required to burn the fuel properly. Mr. P. A. Lennertz, who had charge of building of eleven tank steamers for Nobel Brothers, in Russia, says: 'I have seen boilers on board ships on the Caspian Sea, which have been left with open air holes in the fire doors after the burners had been shut off, and the result was cracked tube sheets, leaky tubes, steam and stay bolts.'

"9th. To my mind, it is a great mistake for those countries which possess no oil fields to experiment with this fuel for naval purposes. A late review says that Germany has taken this stand, and hereafter, except for purely scientific research, she will not experiment further with the residuum of petroleum as a combustible for the vessels of her navy."

Edward's closing paragraphs of recommendations are also of great interest, summing up, as they do, the state of the problem as of that date:

"With our great oil fields abundantly able to supply a manifold quantity of liquid fuel for naval purposes, it ought to be our policy to supplement the work that has already been done by a series of exhaustive experiments with this residuum as a combustible. The Engineer-in-Chief should be given a torpedo boat and a small gun boat to experiment with, and the investigation of the subject of liquid fuel should be carried on regardless of expense. The naval engineering expert, who would have supervisory charge of the work, would see that, despite the breadth and cost of the experiments, no money was wasted. Nor would he permit the work to be crippled by conducting the investigation after the plans of non-professionals who were incapable of finding out its merits.

"Dissertations upon liquid fuel are a favorite theme of the novice, and some of the material is unintelligible to the naval engineer.

"The solution of this engineering question can only be delayed by having non-professionals interfere with a careful examination of its merits and defects. The engineer alone can realize the possibilities of this incomparable fuel, but he must have facts, and not hopes and promises, to justify him in adopting it as a combustible for naval purposes."

From 1895 to 1901 the adaptation of oil as a naval fuel proceeded very slowly and there is no record of a permanently equipped oil burning man-of-war during that time. The Italian, French, and Russian Navies had all adopted the combination arrangement which had been tested in Italian torpedo boats.

Jane's "Fighting Ships" for 1901 shows that of the eight leading naval powers, England, the United States, Japan, and Austria were not using oil as a fuel on any ships. Germany had two trial installations of coal and oil combined on coast defence vessels. France and Italy each had sufficient ships of all classes fitted for oil as an auxiliary fuel to indicate that those nations had adopted the combination for general application. Russia was divided. Her Baltic fleet was still dependent entirely on coal. Her Black Sea fleet resembled those of the two southern fleets in its general adaptability for burning coal or oil or both.

It is probable that there were experimental installations under test which are not shown in Jane. England is known to have had several and Austria at least one such prior to 1901. These installations were probably of such a temporary nature that their mention in Jane was not warranted.

During this early period, in the United States a considerable amount of thought on the subject was augmented by some experimentation. Engineer-in-Chief E. R. Freeman, U. S. N., in his annual report for 1897 stated that "* * * from 1867 to the present time the Bureau has, at intervals, conducted experiments with various forms of apparatus and kinds of fuel oil. * * *"

It is probable that these experiments were largely, if not entirely conducted on shore. Mention, with no details, is found of some conducted in the Navy Yard at Charleston, South Carolina. In 1888 boards of naval engineers were appointed to conduct two experiments with liquid fuel, one on a naphtha (light gasoline) fired steam generator plant and the other on an oil burning loco-

motive. The former was of little value to liquid fuel progress because the nature of the fuel used was such that it could not be considered for naval use. The final paragraph in the report of the second board, which consisted of Chief Engineer A. S. Green, U. S. N.; Passed Assistant Engineer C. W. Rae, U. S. N., and Assistant Engineer R. S. Griffin, U. S. N., states:

"We are of the opinion that the system could be advantageously adopted on board torpedo boats and coast defence vessels, if safety in stowage and handling can be clearly arranged and think the device * * * worthy of a trial, particularly as it can be applied without interference with the coal-burning arrangement."

This report was published in the report of the Engineer-in-Chief in 1888. Rear Admiral George W. Melville, U. S. N., had become chief of the Bureau of Steam Engineering in 1887. The above quotation, which, as stated, was printed in the second report of Admiral Melville's incumbency is the first *definite* official recommendation made by any naval official urging an actual sea-going oil-burning installation.

There followed a seven-year lapse in official allusions to the subject. In 1895 Admiral Melville recommended that "* * * a series of experiments should be made with petroleum to find out its value for torpedo boats and the smaller types of vessels. * * *" During 1896 successful tests were made using oil fuel in a small torpedo boat carried by the *Maine*. The only point not settled by this test according to the Engineer-in-Chief was elimination of danger in carrying oil. In the same year, the Department authorized oil-fuel installations in a tug building at Norfolk and in Torpedo Boat Number 15 (*Talbot*) building by the Herreshoff Company. What was actually done in connection with the tug cannot be found in the records. When war with Spain appeared as a possibility, the Bureau of Steam Engineering found it necessary to change the *Talbot* to coal burning because the small number of torpedo boats available for war forbade the diversion of one to experimental purposes. It had been hoped by the Bureau that results obtained in the *Talbot* would be compared with those on a sister Herreshoff boat burning coal and thereby settle some of the undecided questions.

During the war with Spain, opportunity was found to install an oil burning plant on the *Stiletto,* a small torpedo boat belonging to the Bureau of Ordnance. The installation was made and operated under the direction of Passed Assistant Engineer John C. Leonard, U. S. N., and was considered successful. However, shortly after the boat was returned to the Bureau of Ordnance at Newport, the commandant at that station reported that it was more expensive and less satisfactory than when burning coal and the installation was removed. The Bureau of Steam Engineering considered that the apparent failure was due to "indifference or lack of acquaintance on the part of those who handled it."

The Naval Appropriation Act for the fiscal year 1899 carried one item for "Experiments with liquid fuel on steam tug, New York Yard; experiments with liquid fuel on two torpedo boats, $15,000." This appropriation appears to have been anticipated by the Department by about two years.

In 1899 the tests originally planned on the *Talbot* were finally begun and promised at first to be very encouraging. However, after a year, the various systems which had been tried gave very discouraging results in at least two particulars. No more than three-fourths of full power could be developed and that only for very short periods; and at speeds above ten knots the smoke nuisance was as serious as it was when burning soft coal. The experiments were then largely transferred to an air-tight fireroom which had been built in the New York yard in order that waste effort on unsatisfactory installations afloat could be eliminated.

The work in New York was continued with apparently no definite results for two more years. The first period of scattered experimentation was hurried to an end by the spectacular discovery of the Spindletop Field in Texas in 1901. At about the same time large new fields were opened up in California.

One of the things which had been responsible for a great lack of support for fuel oil had been the uncertainty of the supply. Why go to considerable expense and effort to find out if oil could be used when it seemed probable that there would be insufficient of the oil available if it was wanted? Now there was a flood of oil with the prospect that it would be maintained or increased for a long time into the future and the Navy was not yet in a position to decide whether or not it wanted the oil.

The change from uncertainty was heralded by three lines in the Naval Appropriation Bill for the fiscal year 1903, approved 1 July 1902. These lines read:

"Tests of liquid fuel for naval purposes: For extended tests of liquid fuel from the California and Texas oil fields under the direction of the Bureau of Steam Engineering, Navy Department, twenty thousand dollars."

II. 1902 TO 1904—THE NAVY LIQUID FUEL BOARD.

This interval of only two years is set aside as a definite historical period because the work accomplished in twenty-four months by the Navy Liquid Fuel Board stabilized the entire problem and definitely led to the eclipse of coal as a naval fuel. The spasmodic and indefinite experimentation of the nineteenth century was succeeded by a set of tests, scientifically planned and executed. The Board's report placed in the hands of responsible naval authorities engineering data such as neither of our own nor any other Navy Department had.

The twenty thousand dollars appropriated for liquid fuel tests had been urged by Admiral Melville for several years and when it was made available, the Bureau of Steam Engineering was ready. The water-tube boiler question had been one of the most difficult and controversial of the engineering problems which was rife at the turn of the century. In 1901, the Oil City Boiler Works had erected a boiler in Washington. They were anxious to have its suitability for naval use determined. The Bureau, equally anxious to find satisfactory water-tube boilers and in this case relieved of financial responsibility by the exhibitor, willingly appointed a board of engineers to test the boiler. This board was headed by Commander John R. Edwards who has been previously mentioned. The other members were Lieutenant Commanders W. M. Parks and F. H. Bailey, U. S. N.

The boiler was all set up and had been thoroughly tested using coal. The board had set up a test procedure which became a model for all subsequent similar tests. The members of the board, all experienced engineers and freshly experienced in the exhaustive series of coal-burning tests, were all ready to take up the liquid fuel problem.

No very detailed account of the work of the board is necessary. Those who would study the details need only to refer to any engineering journal of the years 1903 or 1904 to find full accounts. There is also available the interim report printed in full as an appendix to the annual report of the Engineer-in-Chief of 1902 and the final report of the board published and widely distributed in 1904. The report stands out as one of the world's finest engineering classics and gives a model which has been followed by later reports on boiler performance and operation. Among other things, the report has been styled "the Bible on liquid fuel of the *British* Admiralty. Twenty-five years after its publication, the Bureau of Engineering still received occasional requests for copies of it.

After a thirty-month study, which covered both the coal and oil burning tests, the board reached the conclusion that the engineering problems of oil burning had been solved. Unfortunately, the board limited its real experimentation to atomizers using steam. Some spraying tests of mechanical atomizers were made and the board recognized the superiority of this type of atomizer for marine use, but it made no specific recommendation concerning them.

The final chapter of the report contains the board's conclusions which are divided into thirty-three paragraphs. Of these, twenty-three cover strictly technical engineering features. It is not the intention of this paper to discuss the mechanical problem and developments in oil burning except where they have seriously affected the general problem. The ten paragraphs which discuss questions of a strategic or military character are quoted as of particular interest after an interval of thirty years.

"5. That the evaporative efficiency of crude and refined oil is practically the same, no matter from what locality the oil may come. The danger of using crude oil, however, is much greater. As it should not be an expensive matter to build refineries near one of the terminal points of a pipe line, the expense of such refining should not increase to a perceptible degree the cost of such fuel, since the sale of the by-products of crude oil would often pay in great part the expense of distillation.

"13. That no design of oil-fuel installation should be permitted for marine purposes which would not permit the renewal within twenty-four hours of all grate and bearing bars, so that a return to coal could be accomplished within a reasonable time in case of failure of oil supply.

"16. That marine firemen are not ill-disposed toward the use of oil. It will be essential, however, particularly for marine use, to secure intelligent men for the operation of the burners. It will be found that resulting financial economy will ensue by intrusting the management of oil-fuel installations to men of skill and judgment. Cheap labor can not be employed in the work; there will be resulting damage, annoyance, and danger if the operation of oil-fuel burners is assigned to unskilled labor.

"19. That in the stowing of liquid fuel on board vessels, whether taken on board for fuel purposes or for transportation in bulk, the compartments containing the crude product should be as few as possible, both for reasons of safety and for facility of delivery and discharge.

"20. That with the use of oil the forcing of a marine boiler should be much more readily accomplished than with the use of coal.

"21. That under severe forced-draft conditions and with water-tube boilers and with the use of oil as a fuel, the solution of the smoke question is nearly as remote as ever. Where a limited quantity of oil is burned in a Scotch boiler, however, and retarders are used in the tubes the burning crude petroleum should be smokeless.

"29. The importance and necessity of always possessing a reserve supply of superior fuel were strikingly impressed upon the board, for during both the coal and oil experiments there was resulting delay due to the nondelivery of fuel. * * * The necessity of maintaining at every naval station a large invoice of hand-picked coal of the very best quality, to be utilized for emergency and experimental purposes, was repeatedly emphasized. As for a reserve of coal for war purpose, it is highly probable that in a contest for the command of the sea an adequate reserve of fuel may be only one remove in importance from the possession of a reserve of ships.

"30. In view of the fact that 48 per cent of the world's output of crude petroleum is produced in the United States, and that practically our entire yield is secured from fields which are in pipe-line communication with important maritime and strategic ports, the board considers that a joint commission, representing commercial, manufacturing, maritime, and naval interests, should be authorized by the Congress, whose province it would be to formulate such rules and regulations as would provide for an economical, efficient, enduring, and safe oil-fuel installation. Heretofore the oil-fuel problem has been principally investigated by various individual interests which have sought to secure information along certain lines. As a result there has not been obtained that knowledge of the subject which would be warranted, considering the natural advantages possessed by the United States in having at its command near great seaports such a large proportionate supply of the world's production of the crude product. Particularly for the development of our commercial interests in the Gulf of Mexico and on the Pacific coast should the work of such a commission have an important influence in extending our prestige and power, whether viewed from a commercial, maritime, or naval standpoint.

"31. The board regards the engineering or merchanical feature of the liquid-fuel problem as having been practically and satisfactorily solved. For manufacturing purposes the financial and supply features are the only hindrances to the use of crude petroleum as a standard fuel. For mercantile purposes the commercial and transportation features of the problem are existing bars which limit the use of oil fuel in merchant ships. For naval purposes there is the additional and serious difficulty to be overcome of providing a satisfactory and safe structural arrangement for carrying an adequate bunker supply.

"32. That in the consideration of the problem of attempting to use oil as a fuel for either marine or naval purposes it should be particularly remembered that, by reason of the economic and commercial demands for crude oil for illuminating, lubricating, and other purposes, the available supply of the world's production of crude petroleum that could be used as a fuel would not meet over 3 per cent of the world's demand for coal and other

combustibles. For a time, therefore, the effort should be made to use oil fuel only for special purposes in particular localities."

The board estimated that a quarter of a million dollars had been spent on the tests. Only twenty thousand dollars had been appropriated but this was augmented by a balance of seven thousand remaining from a previous appropriation. The remainder represents the expenditure of the various commercial exhibitors of boiler and burners.

During the progress of the liquid fuel tests one naval officer, not a member of the board, became identified with it and from that date was intimately connected with many of the steps in advance made by the Navy in the use of liquid fuel. This was (then) Ensign John Halligan, Jr., U. S. N., Commanding Officer of the U. S. S. *Rodgers*. The *Rodgers* was stationed at Washington along with the *Gwin* for about a year during the tests in order that their crews would be available for assisting the board. The officers and crews, with particular mention of Ensign Halligan, were highly commended by the board for their work.

The encomiums of the board on the enlisted personnel who assisted them constitute a striking tribute to the naval enlisted man of that date in view of the comments contained in paragraph 16 quoted above. Apparently the board found the crews to be men of intelligence, skill, and judgment.

While the United States was awaiting the result of the liquid fuel tests, other navies were making some progress. At least three successful mechanical atomizers for oil burning had been developed, one each in England, France, and Germany. A number of installations were made.

In 1901, the German Navy completed the *Kaiser Freidrich III*, a battleship. She carried oil as an auxiliary fuel. The German decision to stick to coal because of her lack of domestic supply of oil was short-lived under the pressure of military advantage. On her trials, the *Kaiser Freidrich III* grounded amidships. The damage to the ship in grounding was not great but the accident ruptured the fuel oil tanks which were located in the double bottoms under the firerooms. Oil was forced up into the firerooms which were steaming on coal at the time. An oil fire ensued which

drove the crews out of the firerooms and caused more damage to the ship than had the grounding itself. As a result of this very early disaster, the utilization of the fireroom double bottom compartments for carrying fuel oil has been forbidden right down to the present.

In 1902 it was announced that oil had been adopted as an auxiliary fuel for British battleships and that the *Mars* and *Hannibal* had been so fitted. It was during this same year that the first mechanical atomizer was tried in the British *Sithonia*.

During 1903 another of our present safety precautions was born. The S. S. *Progreso* was destroyed by an oil fire in San Francisco. So many of those who should have made good witnesses failed to survive the catastrophe that it was impossible to definitely determine the cause. One supposition was that riveting was being done on the top of the tank containing oil vapors and that a hot rivet had exploded these vapors. Neither the supposed riveter nor his equipment could be found among the debris after the fire so the fact was not established. However, the possibility was visualized and the indicated safety rule was written into the book.

During 1903 also, another of Admiral Melville's hopes was realized. Congress appropriated funds for the establishment of the Engineering Experiment Station at Annapolis. This fact is mentioned because it was stated that one of the functions of this laboratory would be a study of the oil fuel problem. As a matter of fact, the Experiment Station was soon loaded with so many other problems that the oil fuel question was never approached.

III. 1904 TO 1910—EARLY APPLICATIONS.

It was probably not the report of the Liquid Fuel Board which was directly responsible for the adoption of oil fuel. The Engineers-in-Chief Melville, Rae, and Cone could and probably would have effected the change anyway. However, the report gave them the engineering data which thy needed for ammunition and for their own reassurance.

The Liquid Fuel Board had recommended that fuel oil installations be made on a coast defense monitor on the Pacific coast and on several torpedo boats on the Atlantic.

The Navy Department adopted a policy which differed from that recommended and also differed from and was more rational than that of any other Navy. While others were altering old ships to fit them for burning oil, the United States Navy came to a definite decision and, with one exception, made the application only to new ships. Thus the burning of oil was included in the original design of practically all ships which used the liquid fuel.

In 1906 the Department authorized an oil burning installation on the monitor *Wyoming* whose name was subsequently changed to *Cheyenne*. The installation was not completed until 1909. To the Bureau of Steam Engineering the *Cheyenne* was an engineering success but was not absolutely satisfactory for two reasons. In the first place, the system used was a commercial one which used compressed air for atomization and required heavy air compressor equipment.

The other objection seems to have been based on the conclusions as regards application of fuel oil which had been reached by the various interested people in the Department. In 1906 the Chief of the Bureau of Equipment mentioned the plans for the *Wyoming* and then discussed at length the advantages to large ships of having both oil and coal burning facilities. These remarks are quoted from the report of 1906:

"A battleship with double bottoms constructed for carrying fuel oil would be able at all times to carry a reserve supply of fuel without in any way interfering with the space required for other purposes or materially reducing her coal capacity. The necessary apparatus for changing from coal to oil in the boilers, or for using oil in case of emergency to increase the efficiency of coal, could be carried.

"Such a vessel held in readiness to sail at short notice could burn oil in port and leave with her coal bunkers full. The oil thus used could be replaced from time to time in a short time without necessitating the cleaning up which always follows coaling. The necessity of removing ashes would also be avoided if oil were always used in port.

"As fuel oil can be obtained in a very limited number of places, as compared with coal, and as the general use of oil as fuel for

steaming purposes would soon reduce the supply to such an extent that the price would become prohibitive, the Bureau is of the opinion that the designs for new vessels for the Navy should accord with the practices which now obtain with regard to the allotment of space for the stowage of coal.

"But as the oil carried in the double bottoms of a battleship would be equivalent to several hundred tons of coal, and increase the steaming radius proportionately without occupying space required for other purposes, the Bureau recommends that in all future battleships the double bottoms be constructed with the view of carrying oil in them, and that all necessary pumps, pipes, and appliances for burning oil be placed on board."

In commenting on the *Cheyenne* test the Chief of the Bureau of Steam Engineering, H. I. Cone, said:

"Gratifying as have been the results obtained with this system, it is not the most desirable for use in naval vessels * * * on account of the desirability of having the heavier vessels so fitted that either coal or oil or both fuels in combination, may be used, as desired, as coal can be obtained everywhere a ship may go, while the ports where oil fuel may be obtained are limited."

The year 1907 marked the beginning of the real fuel oil era. On the sixth of August contracts were let for the construction of battleships 28 and 29, the *Delaware* and *North Dakota*. Included in the specifications for these vessels was the paragraph: "Provision will be made for burning fuel oil in the furnaces." The detailed specifications were given separately on plans of the Bureaus of Construction and Repair and Steam Engineering and no copies of these plans are on file. The specifications also included the usual provisions about coal burning. The oil burning was intended to be additional and auxiliary to the conventional coal burning.

The one feature of the detailed plans which upset the shipbuilders was the requirement that mechanical atomization, without the use of steam or compressed air be used. There was not a single burner of the type required available in the United States. Upon receiving the specifications, each of the interested shipbuilders sent representatives to Europe by the first available transportation. These representatives returned with three types

of mechanical atomizing burners—the Thornycroft from England, the Normand from France, and the Schutte-Koerting from Germany.

The department's demand for mechanical atomization was caused by the success of the European systems and by the desire to force development in this country. An officer attached to the Bureau of Steam Engineering had been detailed to visit Europe to report on recent improvements in marine engineering. He brought back information concerning mechanical atomizers. By direction of Real Admiral Rae, the Engineer-in-Chief, several experimental burners of this type were manufactured and tested at the Brooklyn and Norfolk Navy Yards. When the Bureau was convinced that mechanical atomization was a practical success, its use became a requirement of the specifications. The freedom from waste of steam and heavy compressor equipment were highly desirable and the Bureau of Steam Engineering is worthy of credit for forcing American engineers to discard the then accepted successful methods of burning oil for the much more logical and satisfactory one for marine use.

1908 saw two more shipbuilding machinery specifications requiring fuel oil installations. In September, those for the *Florida* and *Utah* were issued. These specifications repeated the requirements quoted above but included the details. The battleship policy was now established for new vessels of this class but it was never applied to older vessels. The *Arkansas* and *Wyoming* specifications in 1909 and those for the *New York* and *Texas* in 1910 followed the same general lines as regards oil burning as the two previous classes. In all eight of these ships each boiler was fitted for burning both coal and oil, either separately or together.

Admiral Cone, commenting on the early experience with the first of these ships in 1910, said that satisfactory burning of the oil could not be obtained in boilers which were designed with the relatively small combustion spaces required for coal. The oil installation did not, nor was it intended to, increase the power which could be developed. It was intended merely to relieve the firemen on protracted runs at high power or when trimming coal into the bunkers became difficult and also to permit development of full power with dirty coal fires.

It is apparent that practically none of the real advantages of fuel oil could be obtained with the coal-oil combination. It was necessary to retain the valuable space outboard of the fire rooms for coal stowage; a full crew of stokers and coal passers had to be carried; and not only was the usual heavy coal and ash handling equipment still required, but all of the oil burning equipment took up additional space and weight.

As a much more desirable application of oil burning with some of its advantages while still retaining the security of coal, it was suggested and very strongly advocated by some naval engineers that battleships be provided with one-half or one-third of their boilers equipped for burning oil only and the remainder for coal only. This would permit taking fractional advantage of the weight, space, and crew saving superiority of oil, and where used the oil would be burned in properly designed furnaces under optimum conditions. This system might have had a trial and would have been a logical step toward the all oil-burning battleship except that the success of the destroyers led the department to omit that step and to pass directly to the capital ship having sole dependence on liquid fuel.

A few months in advance of the *Utah* and *Florida* the specifications for torpedo-boat destroyers Numbers 22 to 31 were issued. The Liquid Fuel Board had recommended that a number of torpedo boats be fitted for burning oil. However, in 1898 the torpedo boat class, as a result of war experience, was superseded by the heavier and more powerful torpedo boat destroyer. Other navies continued to build both types but the United States dropped the smaller vessel entirely. Sixteen destroyers had been authorized in 1898 and five more in 1907. These were all coal burning and were never altered. For this type of vessel the transition from coal to oil was made abruptly by the specifications mentioned above for the *Paulding* class. These vessels carried neither coal nor coal burning and handling equipment.

This historical period closes with a definitely established policy for the United States Navy as regards the use of fuel oil. Oil alone was to be used hereafter for destroyers and coal with oil as an auxiliary for battleships. Submarines had used liquid fuel from the beginning, a change from gasoline to heavy oil having

taken place due to the development of the Diesel engine. However, it is desired to restrict this paper to the history of fuel oil *burning*. Diesel engine utilization will therefore not be mentioned again.

Prior to 1909, the Bureau of Equipment, Steam Engineering, and Supplies and Accounts had shared the fuel problem. The Bureau of Equipment had been charged with the storage, handling, and transportation; Engineering prepared the specifications, inspected and used the fuel on board ship; and Supplies and Accounts purchased it. In 1909, the Bureau of Equipment was abolished by the Secretary of the Navy and its functions were divided between other Bureaus. Storage facilities for fuel were transferred to Yards and Docks and handling and transportation to Navigation which at that time included the functions of the present Bureau of Navigation and the Office of Naval Operations.

The Bureau of Equipment had preliminarily planned for the supply of oil fuel as needed. The first actual steps taken toward this supply were taken after the change in organization. The naval appropriation for 1904 changed the wording under the heading "Coal and Transportation" from "coal" to "coal and other fuels," thereby permitting the purchase of fuel oil when and if needed. Previous legislation had authorized the Secretary of the Navy to provide for the storage of coal and *other fuels* in such places as he considered necessary and desirable. Appropriations for carrying out this law were made from time to time.

When it became necessary to provide for a supply of fuel oil, there were no legal bars to taking the necessary steps. In 1910 construction of fuel oil storage tanks was started under the Secretary's authorization at a number of points on the Atlantic coast and the Bureau of Supplies and Accounts entered into the first contract for the supply of fuel oil.

In 1910 the situation in the eight leading navies of the world was about as follows: The three general classes of ships considered are battleships, cruisers, and destroyers.

	Battleships	*Cruisers*	*Destroyers*
England	Oil and coal	Oil and coal	Oil (b)
United States	Oil and coal	Coal	Oil
Germany	Oil and coal	Oil and coal	Coal
Japan	Coal	Coal	Coal
France	Coal (a)	Oil and coal	Oil
Italy	Coal (a)	Oil and coal	Oil and coal
Austria	Coal	Coal	Coal
Russia	Oil and coal	Coal	Oil and coal (c)

(*a*) Many ships built prior to 1900 still were listed as being equipped for burning oil and coal but all new battleships since that date carried coal only.

(*b*) Starting in 1906 all destroyers had been built for oil alone. However, in 1909 the Admiralty, worried by the fear of a fuel oil supply failure, reverted to coal for the G-class destroyers designed in that year.

(*c*) Russia had gone to all oil burning destroyers earlier but for her latest vessels of this class she had reverted to the oil and coal combination.

THE TREND IN NAVAL ENGINEERING.

Alternating Current Motors and Generators.

Part 2—Motors.

By C. Huey, Civil Member.*

There is a fairly large number of *types* of A.C. motors in general use in commercial industries. Naval or marine service in general, has no special requirements which necessitate the development of types not already to be found in commercial applications. The performance characteristics of commercial designs of A.C. motors, appear to be just as applicable to naval installations as to the many diversified commercial applications.

Special *material* requirements, however, are desirable for marine service such as non-corrodible metals, non-hygroscopic molded insulations, and oil and water-proof insulating varnishes. For naval ships, the increasing use of the lighter metal alloys, such as aluminum, is being realized more and more to reduce the weights wherever practicable.

In discussing commercial types of A.C. motors likely to be used in naval applications, the scope can be narrowed by considering only *single* and *three-phase* motors. Single-phase motors are suitable for fractional horsepower demands for duty equivalent to domestic applications, and three-phase motors are suitable for all other power applications.

GENERAL CLASSIFICATION OF MOTORS.

The general classification of *single* and *three-phase* motors, based on commercial designs, are named here in order of importance and will be separately described as to their operating principles and performance characteristics.

* Material Engineer, U. S. Navy Yard, New York, N. Y.

(*a*) *Three-phase Induction Motors.*—When A.C. is introduced to the stator windings, a rotating magnetic field is produced. As a result, a drag is set up between the field and the current induced in the secondary winding on the rotating element. Commercial sizes range from ¼ H.P. to 200 H.P. and upward.

(*b*) *Single-phase Induction Motors.*—These belong to the same general class as (*a*), but have special means of securing starting torque which normally is non-existent. Commercial sizes range from 1/6 H.P. to 10 H.P.

(*c*) *Single-phase, Series, Commutator Motors.*—These are practically the same as D.C. series motors in general features of construction and performance, but with laminated field frames to reduce the magnetic losses caused by A.C. excitation. Commercial sizes range from 1/200 H.P. to ½ H.P.

(*d*) *Synchronous Motors.*—These are the same in general features as synchronous A.C. generators, operating as motors. They require direct-current field excitation. Commercial sizes range from 40 H.P. to 200 H.P. and upward.

THE THREE-PHASE INDUCTION MOTOR, PRINCIPLES OF OPERATION.

This type of motor has a wide field of application on account of its performance characteristics which are generally similar to the D.C. shunt motor. In describing the principles which cause this type of motor to start under load and revolve at a speed which is always less than its synchronous speed, it is necessary to discuss the *revolving field* produced by polyphase currents and the resultant magnetic drag set up in the rotor. This in turn causes the *rotor* to follow the polyphase rotating field of the armature or stator.

Polyphase currents such as the two-phase, three-phase or any multi-phase, when introduced into the primary windings of an induction motor, produce a rotating field. The one produced by two-phase currents is the least difficult to describe and will be illustrated and discussed as being applicable in general theory to three-phase currents.

Figure 1 shows two equal sine wave currents of a two-phase (or quarter phase) system. The maximum current has been assumed

as 10 amperes. On the basis of sine waves, the values of the selected intermediate points are 7.07 amperes. The vertical lines marked 2, 3, 4, 5, 6, 7, 8, 9 and 10, designate instants of time referred to in the subsequent Figures.

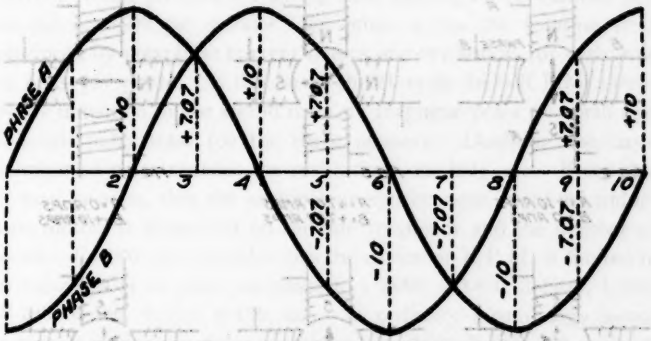
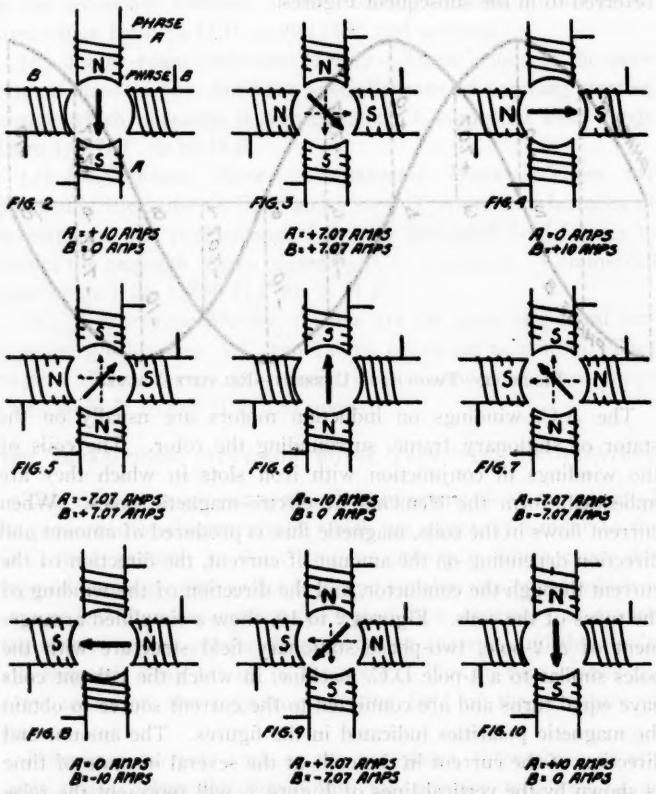


FIGURE 1.—TWO-PHASE CURRENT—RELATIVE VALUES.

The A.C. windings on induction motors are usually on the stator or stationary frame, surrounding the rotor. The coils of the windings in conjunction with iron slots in which they are imbedded, form the elements of electro-magnetic poles. When current flows in the coils, magnetic flux is produced of amount and direction depending on the amount of current, the direction of the current through the conductor, and the direction of the winding of the turns of the coils. Figures 2 to 10, show a simplified arrangement of a 2-pole, two-phase stationary field structure with the poles similar to a 4-pole D.C. machine, in which the current coils have equal turns and are connected to the current source to obtain the magnetic polarities indicated in the figures. The amount and direction of the current in the coils at the several instants of time as shown by the vertical lines of Figure 1, will represent the relative amount and direction of the magnetic flux in the coils of phases A and B. Based on the resultant north or south pole magnetic polarity, the dotted arrows in Figures 3, 5, 7 and 9, show the direction of the magnetic flux from each phase, while the solid arrows in the same Figures show the direction of the *resultant* of two fluxes when at right angles to each other. In Figures 2, 4,

6, 8 and 10, the solid arrows show the direction of the flux when one phase is at its maximum current at which time the current in the other coil is zero.



FIGURES 2 TO 10.—ILLUSTRATING THE ROTATING POLYPHASE MAGNETIC FLUX.

THE ROTATING MAGNETIC FIELD.

By observing the position of the solid arrow in the foregoing set of Figures, it will be seen that the resultant magnetic flux produced by the two currents acting together, has been revolving counter-clockwise and one revolution has been completed. In other words, a rotating magnetic field is being produced by poly-

phase currents, but without the motion of any material part. By reversing the direction of current in one phase, the opposite direction of rotation is produced. In rotating the field one revolution, each current completed one cycle. Hence a 60-cycle, two-phase current would produce a rotating field making 60 revolutions per second or 3600 per minute. In other words the rotating field produced by polyphase current makes one revolution for each *pair* of poles *per phase*. On this basis, the 60-cycle 3600 R.P.M. *three-phase* induction motor would have six magnetic poles (3 north and 3 south poles total for the three phases). Doubling the basic number of poles reduces the revolutions one-half, etc. From this it may be seen, that the nominal or synchronous speed of induction motors is dependent on the line frequency and the number of poles. For 60-cycle installations the choice of R.P.M. is limited in terms of pairs of poles per phase to 1-3600, 2-1800, 3-1200, 4-900, 5-720, 6-600, 7-514, 8-450, etc. In ordinary terminology motor ratings are given in *poles* per phase, *e.g.* 3600 R.P.M. 60-cycle, 2-pole. On the above basis, it is possible without operating them, to determine the *basic* speed of induction motors by counting the number of poles. In actual practice, the poles are not wound and are not projecting as shown in Figures 2 to 10, for the reason that the magnetic flux would be very uneven in distribution from point to point. The commercial form of a three-phase stator assembly is shown on Plate A, in which the insulated windings are imbedded in slots formed by laminated, punched steel sheets, riveted together and secured in a supporting iron or steel frame. The actual number of poles is determined not by the number of coil slots, but by the *pitch* of the coil winding in the slots.

The revolving part or the *rotor* of the motor, consists of a laminated iron core and a short-circuited or partly short-circuited winding. The revolving magnetic flux of the *stator,* induces secondary currents, as in transformers, and by its magnetic action upon the flux produced by these secondary currents, exerts a torque which makes the rotor follow the revolving flux. This phenomenon is similar to a classic experiment of a pivoted disk of copper which follows the poles of a revolving magnet. It also follows the general law of magnetism in the reduction of flux to the shortest path as evidenced by the closing-up pull of an iron

armature when placed in front of the poles of a horseshoe magnet. The rotor of the induction motor never reaches synchronism with the revolving field of the stator, for the reason that if it did, its conductors would be rotating *with* the flux and would not be *cutting* the flux. Therefore no induced currents would be generated in the rotor. In other words, the rotor must lag behind the synchronous speed in order to function. The amount which it lags is dependent on the mechanical load imposed on the rotor shaft. At no load, the speed is very nearly synchronous for the reason that very little torque is required. As the load increases, the rotor lags sufficiently to balance the induced currents and the required torque. The amount which a rotor lags behind the speed of the revolving field is known as *the slip*. It is expressed in per cent by the formula—

$$\frac{\text{(synchronous speed—actual speed)}}{\text{synchronous speed}} \times 100 = \text{per cent slip.}$$

Ordinarily the windings on the rotors of induction motors are of heavy copper or aluminum bar construction, lightly insulated from the magnetic core so as to reduce the parasitic induced currents to a minimum, and to direct the main induced current in paths which are effective in cutting the revolving flux of the stator. In the usual form of rotor, the bar conductors are permanently connected to end-rings, in common with all the bars. These serve to complete the current paths of the conductors. This form of rotor is known as the *squirrel-cage* induction motor on account of the similarity in mechanical construction.

FORMS OF INDUCTION MOTOR ROTORS.

In order to control the speed-load characteristics, the starting torques and starting currents of induction motors, the rotor windings are designed in many ingenious forms in order to limit the induced secondary currents to values which will obtain the results desired. The effect of changing the amount of induced currents is to increase or decrease the rotor slip. The methods used in this control are classified and defined as follows:

(*a*) *Squirrel-cage form,* in which *single* imbedded bar conductors are placed on the rotor core and all connected together at each end by a copper or aluminum ring (see Plate B).

AMERICAN SOCIETY
NAVAL ENGINEERS.

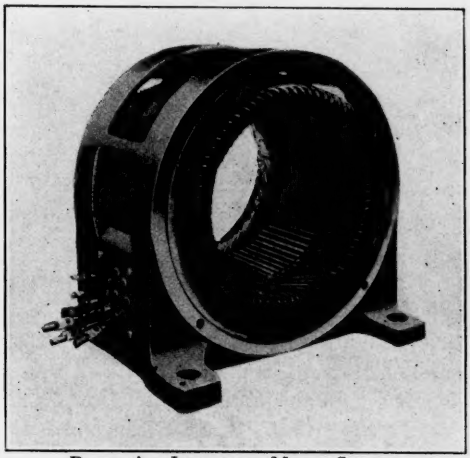


PLATE A.—INDUCTION MOTOR STATOR.

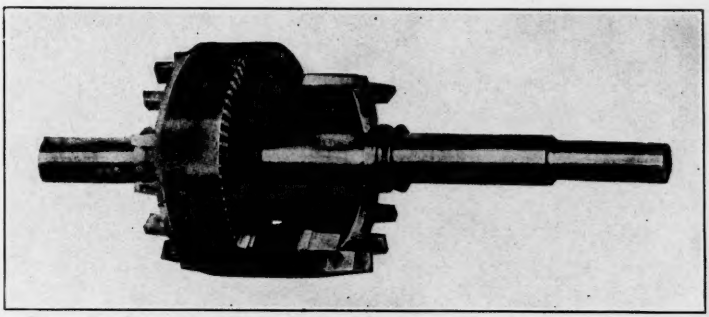


PLATE B.—INDUCTION MOTOR ROTOR (CUT-AWAY VIEW), SINGLE SQUIRREL-CAGE.

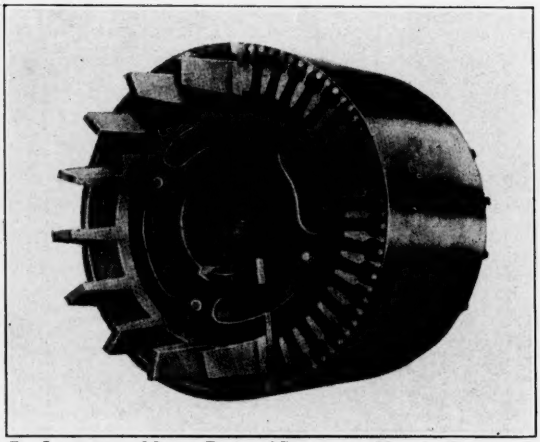


PLATE C.—INDUCTION MOTOR ROTOR (CUT-AWAY VIEW), DOUBLE SQUIRREL-CAGE.

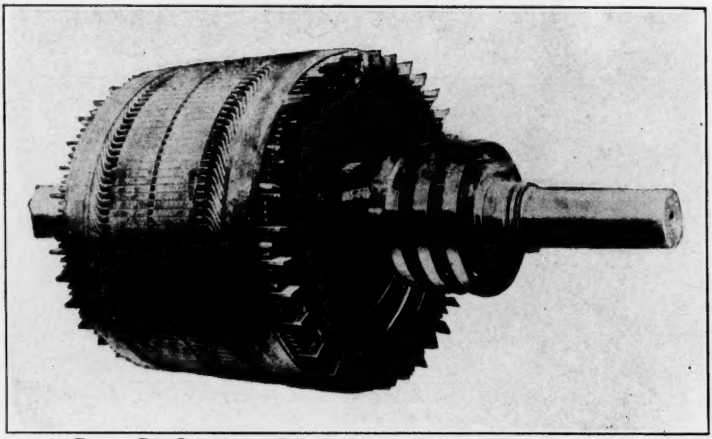


PLATE D.—INDUCTION MOTOR ROTOR, PHASE WOUND-SLIP-RING.

(*b*) *Squirrel-cage form,* in which a *double* set of bar conductors are placed on the rotor core, the one set being of higher resistance and of low reactance. This is superimposed on low resistance high initial reactance main conductors. The outer high resistance conductors function to reduce the starting current and increase the starting torque. At full speed the electrical effects shifts the induced currents to the main conductors which then operates as in class (*a*) (see Plate C) showing a cutaway view.

(*c*) *Coil or phase wound slip ring connected to external resistors.* This form known as the *wound* rotor or slip ring rotor, consists of insulated coil windings generally similar to those of the stator, to the ends of which are connected slip rings, so that external resistances may be included in series for varying the torque or slip (see Plate D).

INDUCTION MOTORS, SQUIRREL-CAGE, THREE-PHASE.

The suitability of the various types of A.C. motors for application to service requirements, depends on two main considerations, viz.; (*a*) the simplicity of the motor and its starting or control equipment; (*b*) the suitability of the performance characteristics of the motor on the basis of its speed and torque under various conditions of machinery demand. For *simplicity,* the *squirrel-cage induction* motor, which has no commutator, slip rings, brushes, and which has only lightly insulated bar conductors on the rotor, is given first preference over all other types of A.C. motors.

The starting schemes for this type of motor is likewise the simplest, as it consists of switching the *stator* or primary windings direct on the power mains at full voltage (see Plate E). Or, if the size of the motor causes voltage disturbance, 50 to 80 per cent reduced voltage is used for the start, obtained (1) from an *auto-transformer* (see Plate F), (2) by changing the stator connection from the Y start to the delta run hook-up, (3) by using primary *resistors,* or (4) by using primary *reactors.*

After the limit of speed is obtained from the starting voltage, the full line voltage is applied. In this form of application, once the motor is on the line, the speed regulation is beyond the control of the operator, and the performance of the motor under its

load becomes a function of the inherent characteristics of the squirrel-cage induction motor.

PERFORMANCE CHARACTERISTICS OF A SQUIRREL-CAGE INDUCTION MOTOR.

A representative set of curves covering the performance characteristics of a general purpose, navy, commercial 7½ H.P. three-phase, 220-volt, 60-cycle squirrel-cage induction motor, is shown in Figure 11.

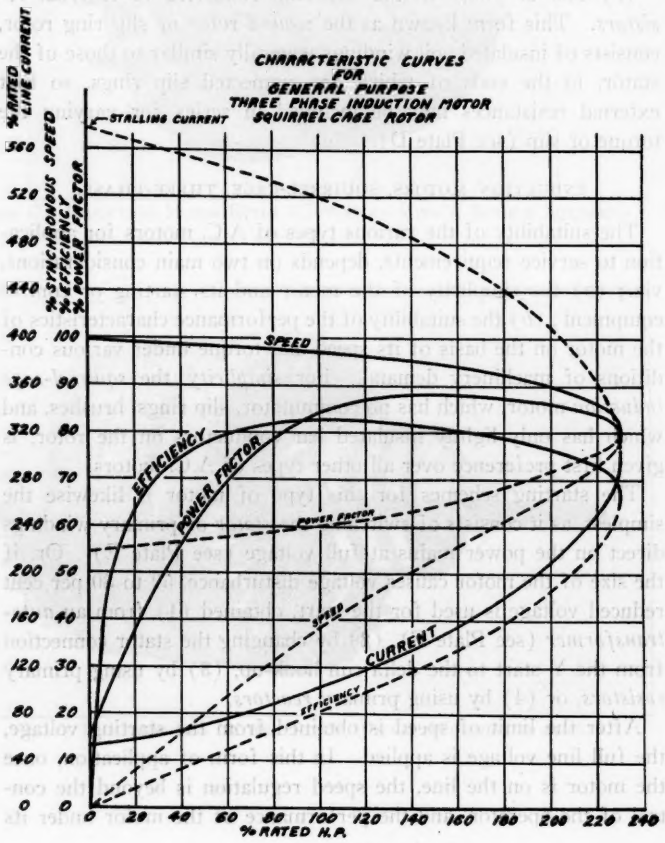


FIGURE 11.

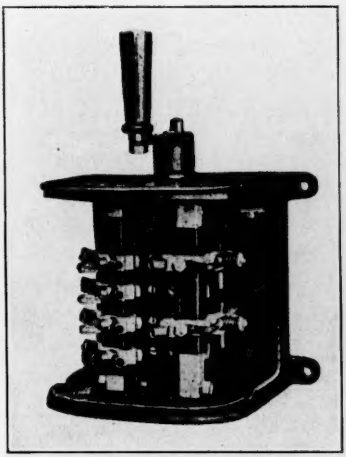


PLATE E.—LINE START DRUM SWITCH FOR SINGLE SPEED MOTORS.

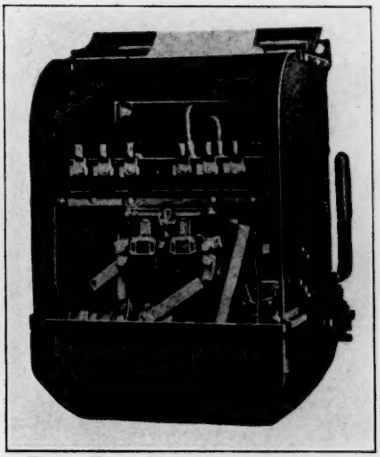


PLATE F. — AUTO-TRANSFORMER STARTER FOR REDUCED VOLTAGE STARTING.

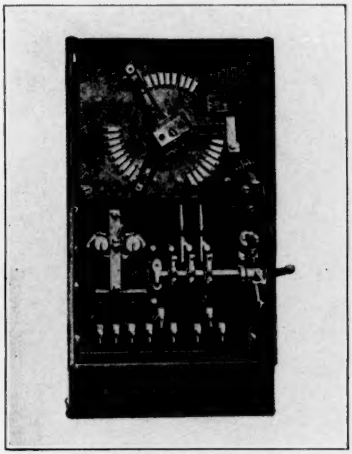


PLATE G.—LINE START SWITCH WITH SECONDARY RESISTORS FOR WOUND-ROTOR INDUCTION MOTOR.

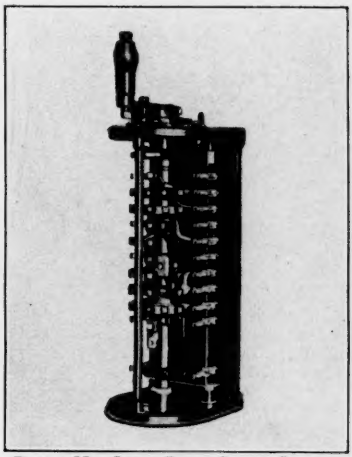


PLATE H.—LINE START DRUM SWITCH FOR MULTI-SPEED SQUIRREL-CAGE INDUCTION MOTOR.

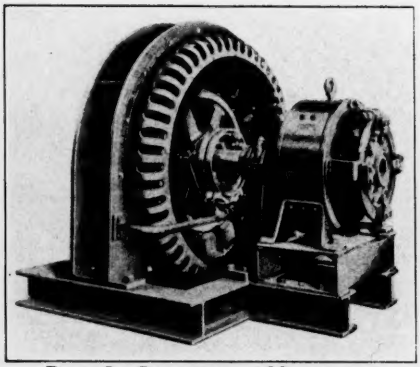


PLATE I.—SYNCHRONOUS MOTOR WITH EXCITER.

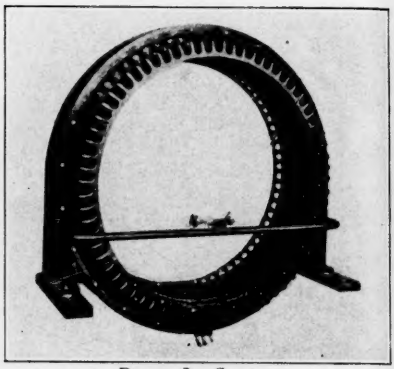


PLATE J.—STATOR.

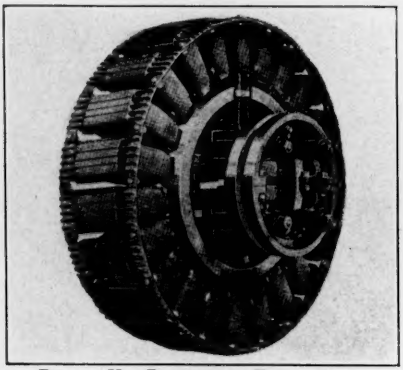


PLATE K.—REVOLVING FIELD ROTOR WITH DAMPER WINDING.

PLATE L.—ROTOR WITH FLY WHEEL.

THE SYNCHRONOUS MOTOR.

In the foregoing curves, it will be noted that at 230 per cent rated H.P., the speed curve bends sharply and then runs to the zero point. The torque corresponding to this bend point is known as the *pull-out torque* point of the motor. It will be also noted that there is a drop in speed of only about 3 per cent from no load to full load, while the power-factor is fairly high for loads greater than about 80 per cent rated H.P. These curves also show the shortcomings of the squirrel-cage induction motor. By referring to the current curve, it will be seen that the no-load current is over 50 per cent of the full load current, while the corresponding power-factor is only about 15 per cent. On most motors the no-load current does not exceed 30 or 35 per cent of the full-load value. By following along the current curve beyond the bend point, to the stalling point of the motor, it will be seen that this point, which may also be called the *starting* current, is about 570 per cent of the full load current. Summarizing the characteristics of the squirrel-cage induction motor in general, establishes the following facts: (1) The *no-load* current is relatively very high and the power-factor is correspondingly low. This indicates that this type of motor should not be used, in any appreciable size, where its work load is light, or where the motor idles for a major part of the time. This is especially so in small power plants where the low power-factor of the idling motors would seriously lower the *plant* power-factor. Also, if power were to be charged on the basis of current, the idling motor might cost to operate nearly as much as a half-loaded D.C. motor. The power-factor of induction motors depends considerably upon their designed speed. In some applications, it is proposed to use mechanical gearing in order to take advantage of the light weight and increased power-factor of the higher speed induction motor and still obtain the moderate speeds required by the driven auxiliaries. (2) The *starting* current, in general, is always very high, especially in the case of a low resistance squirrel-cage rotor, where the speed characteristics are the most uniform. The starting current usually is of the order of 6 to 10 times the full load current. This characteristic is to be recognized when considering starting this type of motor, if of appreciable size, directly across the line in relatively small capacity generating plants. The starting current,

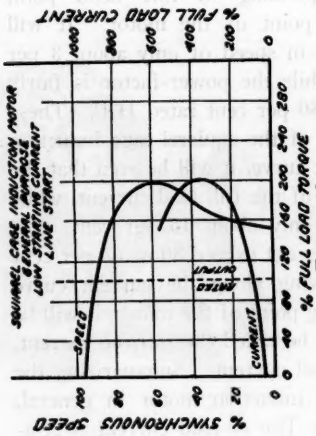


FIGURE 13.

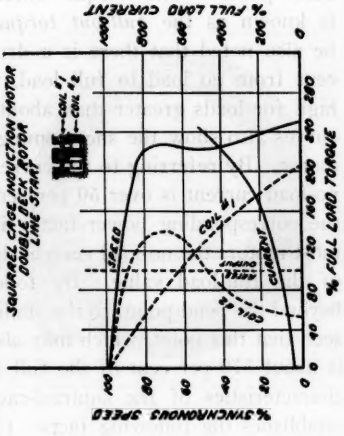


FIGURE 15.

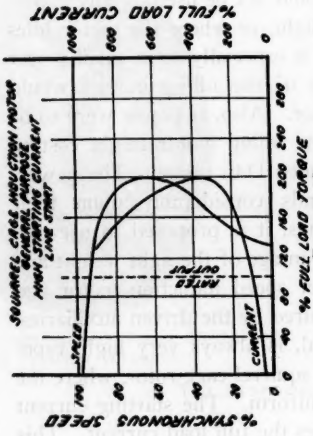


FIGURE 12.

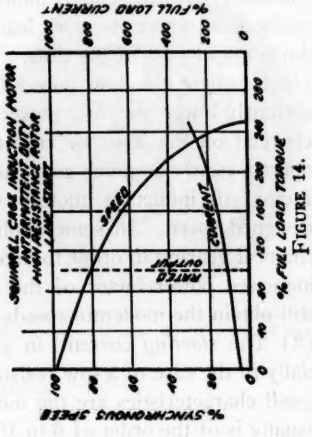


FIGURE 14.

however, is subject to considerable design control which is accomplished, in general, by the amount of resistance incorporated in the rotor squirrel cage.

In general, the higher the resistance of the rotor circuit, the less the starting current. High resistance rotors, due to the I^2R heat generated, are usually restricted to intermittent duty. The *double* squirrel-cage rotor is an exception to this restriction where a *high* resistance starting winding automatically, by change in electrical characteristics, causes the current to shift to a *low* resistance winding when the rotor approaches full speed. The control of the *starting* current by the design of the rotor resistance results also in a marked change in the speed and torque characteristics. This variation in the speed and torque characteristics serves to make the squirrel-cage induction motor applicable to different classes of services, the exact selection of which becomes a matter of experience in the requirement of the machinery to be operated. Figures 12, 13, 14 and 15 show the characteristics of four general types of *line start* squirrel-cage motors in terms of starting current, starting torque, pull-out torque, running current and running speeds, from no load to the stalling point of the motor.

FIGURE 15.

For purposes where these characteristics are unsuitable or where speed *control* is desired, recourse is made to the phase-wound, slip ring rotor type of induction motor, where by the use of external series resistors in the rotor (or secondary) circuits, the starting current, and starting torque characteristics are improved, while the speed performance with various amounts of control resistors in the secondary circuit, is greatly changed from that of the squirrel-cage type. This will be shown in the following paragraph.

THREE-PHASE INDUCTION MOTOR WITH SLIP-RING, PHASE-WOUND ROTOR.

This class of motors necessitates the use of well insulated windings on the rotor, the coils of which are wound to the same polar phase system as the stator. The ends of the windings are brought out to three slip-rings. At these points connections are made by means of carbon brushes and cables, to a three-phase starting or variable rheostat. The diagrammatic scheme of this system is

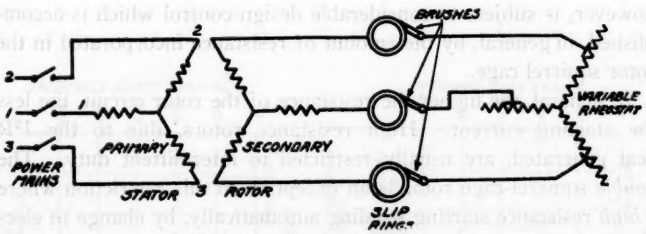


FIGURE 16.—DIAGRAMMATIC SCHEME OF A THREE-PHASE WOUND ROTOR INDUCTION MOTOR.

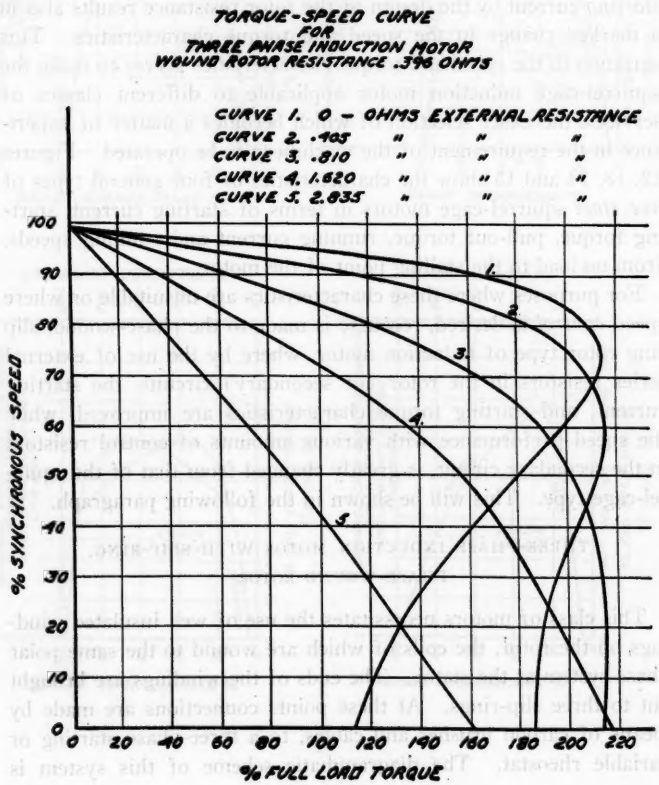


FIGURE 17.

shown in Figure 16, and Plate G shows a typical starter for a small motor in which the start is made by connecting the primary direct to the line while the secondary is connected to the highest resistance point of the rheostat.

The effect of the running performance of the wound rotor induction motor with various amounts of resistances in the rotor external circuit, is shown of a typical motor in Figure 17, in which Ra equals the resistor ohmic value.

In the above characteristic curves it will be noted that in curve 1, when $Ra = 0$ (short circuited rotor), the starting torque is low, while at the upper part of its torque curve, the per cent slip is low. This performance is generally similar and the circuit is equivalent to the squirrel-cage type of rotor. In curves 3 and 4, the standstill torques are high, but the slip values are high. It is evident from the foregoing, that by the use of appropriate values of resistors, the wound rotor, slip-ring type of motor, may be started at various torque values within wide limits, and various speed characteristics may be obtained by the use of a suitable number of control points on the resistors. It is to be noted, however, that the rheostatic power-loss in this form of control, is of considerable relative amount, and in this respect it compares with the rheostatic losses of *series* resistors in the main or armature circuit of a D.C. motor.

MULTI-SPEED, SQUIRREL-CAGE, INDUCTION MOTORS.

It has been shown in the foregoing that speed control of the induction motor may be obtained by employing the *wound* rotor type and external resistors. For many purposes, the power plant losses in the resistors used with large motors, would preclude the use of this system. In addition, the upkeep and cost of this form of equipment are appreciable factors as it necessitates the use of wound rotors, slip-rings and brushes. It has been shown, that the squirrel-cage form of rotor is fundamentally of simplest construction and that the basic speed obtained (at 60 cycles power) is dependent on the number of poles in the stator. This factor has been made use of by motor manufacturers in the design of *stator* windings which, when connected to the line, will produce mag-

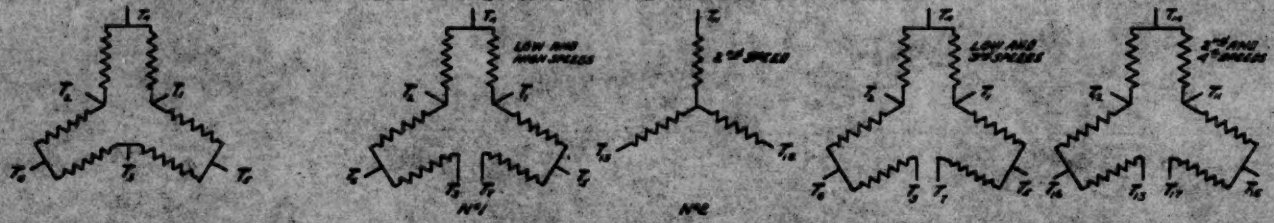
netic poles in various combinations of numbers with resulting multiple basic speeds in terms of these numbers.

Multi-speed windings, in general, are of three types known as (1) the *consequent (or resulting) pole* type in which the number of resulting poles are changed by external *re-connection* which splits the coil groups and divides the winding; (2) the *multiple winding* type (two or more distinct windings) in which *each winding* is arranged to result in a basic number of poles which will obtain different basic speeds; and (3) the type which is the *combination* of the consequent pole and multiple winding types. The combination of speeds from the *consequent pole* type (or divided winding), is limited to the ratio of 2 to 1, *i.e.*, 1200 and 600 R.P.M. or 900 and 450 R.P.M., etc. For the *multiple winding*, the two or more speeds are limited by mechanical considerations, to subcombinations of 3600 R.P.M. The highest speed based on 60 cycle current and the minimum of one pair of poles per phase is 3600 R.P.M. For power drives where variable frequency generators are employed, as in the case of main propulsion systems, the basic speed of the motors also varies directly as the impressed frequency.

To illustrate the flexibility and useful combinations which can be obtained from multi-speed types of squirrel-cage induction motors, the diagrammatic connection schemes shown in Figures 18, 19, 20 and 21 are based on commercial designations. The individual torque, horsepower speed characteristics at each of the speed combinations shown, are in every case, the same as the simple squirrel-cage induction motor (refer to Figure 11).

The connection diagrams are separated into classes to indicate the torque-horsepower-speed relation at the various speeds when applied to the motors. By considering that the speed changes are the result of pole grouping, that the torque varies as the square of the voltage applied to the sections of the coils, and that the horsepower relation is the product of the speed and torque relations, the various systems of stator windings and connections are classified as follows: (*a*) *constant torque motors* for use in printing presses, air compressors, reciprocating pumps, and other similar equipment (see Figure 18); (*b*) *variable torque motors* applicable to equipment such as fans, centrifugal pumps, etc. (see Figure

FIG.18 — CONSTANT TORQUE CONNECTIONS-SINGLE AND DOUBLE WINDINGS



TWO SPEED SINGLE WINDING

SPEED	L_1	L_2	L_3	NOTES
LOW	T_1	T_2	T_3	T_4 T_5 T_6 OPEN
HIGH	T_4	T_5	T_6	T_1 T_2 T_3 TOGETHER

SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
HIGH	1	2	2

THREE SPEED DOUBLE WINDING

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
LOW	T_1	T_2	T_3	T_4 T_5 T_6 T_7 T_8 T_9 T_{10}	NONE
2ND	T_4	T_5	T_6	T_1 T_2 T_3 T_7 T_8 T_9 T_{10}	NONE
HIGH	T_7	T_8	T_9	T_1 T_2 T_3 T_4 T_5 T_6	T_1 T_2 T_3

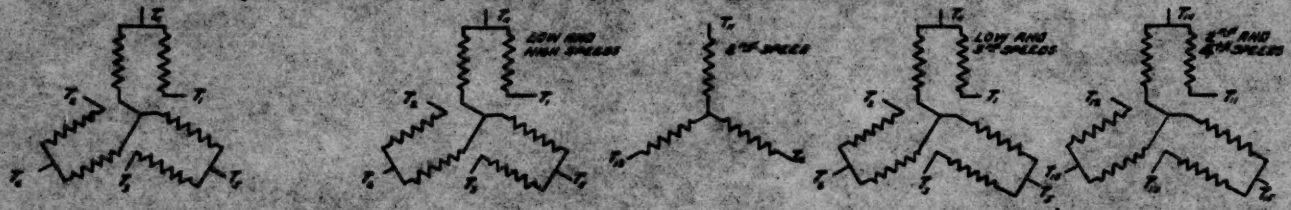
SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
2ND	1	1½	1½
HIGH	1	2	2

FOUR SPEED DOUBLE WINDING

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
LOW	T_1	T_2	T_3	T_4 T_5 T_6 T_7 T_8 T_9 T_{10} T_{11} T_{12}	NONE
2ND	T_{11}	T_{12}	T_{13}	T_1 to T_9 T_{10} T_{14} T_{15} T_{16}	NONE
3RD	T_4	T_5	T_6	T_{11} to T_{16}	T_1 T_2 T_3 T_7
4TH	T_{14}	T_{15}	T_{16}	T_1 to T_{13}	T_{11} T_{12} T_{13} T_{14}

SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
2ND	1	1½	1½
3RD	1	3	3
4TH	1	4	4

FIG.19 — VARIABLE TORQUE CONNECTIONS-SINGLE AND DOUBLE WINDINGS



TWO SPEED - SINGLE WINDING

SPEED	L_1	L_2	L_3	NOTE
LOW	T_1	T_2	T_3	T_4 T_5 T_6 OPEN
HIGH	T_4	T_5	T_6	T_1 T_2 T_3 TOGETHER

SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
HIGH	1	2	2

THREE SPEED - DOUBLE WINDING

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
LOW	T_1	T_2	T_3	T_4 T_5 T_6 T_7 T_8 T_9	NONE
2ND	T_4	T_5	T_6	T_1 to T_6	NONE
HIGH	T_7	T_8	T_9	T_1 T_2 T_3	T_4 T_5 T_6

SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
2ND	¾	¾	1½
HIGH	¾	¾	2

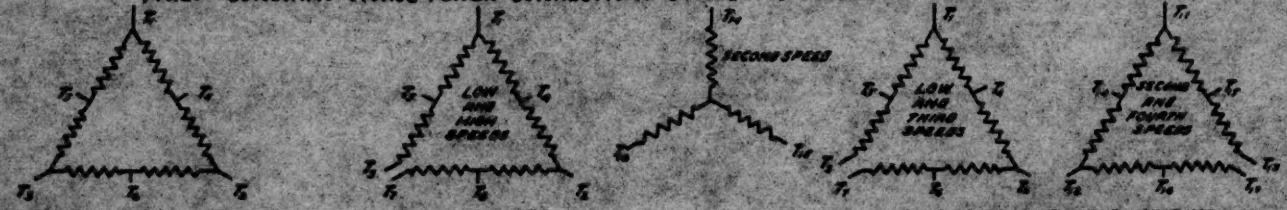
FOUR SPEED - DOUBLE WINDING

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
LOW	T_1	T_2	T_3	T_4 T_5 T_6 T_7 T_8 T_9 T_{10} T_{11} T_{12}	NONE
2ND	T_{11}	T_{12}	T_{13}	T_1 to T_9 T_{10} T_{14} T_{15} T_{16}	NONE
3RD	T_4	T_5	T_6	T_{11} to T_{16}	T_1 T_2 T_3
4TH	T_{14}	T_{15}	T_{16}	T_1 to T_{13}	T_{11} T_{12} T_{13} T_{14}

SPEED	RELATIVE		
	TORQUE	H.P	SPEED
LOW	1	1	1
2ND	1	1½	1½
3RD	1	3	3
4TH	1	4	4

FIG.20 — CONSTANT HORSE-POWER CONNECTIONS-SINGLE AND DOUBLE WINDINGS

FIG.20 - CONSTANT HORSE-POWER CONNECTIONS - SINGLE AND DOUBLE WINDINGS



TWO SPEED GAMBLE WINDING

SPEED	L_1	L_2	L_3	
LOW	T_1	T_2	T_3	T_4 T_5 T_6 TOGETHER
HIGH	T_4	T_5	T_6	T_1 T_2 T_3 OPEN

RELATIVE			
	TORQUE	H.P.	SPEED
LOW	1	1	1
HIGH	2	2	2

THREE SPEED DOUBLE WINDING

SPEED	L_1	L_2	L_3		
LOW	T_1	T_2	T_3	OPEN	T_4 T_5 T_6 TOGETHER
2ND	T_7	T_8	T_9	T_1 T_2 T_3 T_4 T_5 T_6	NONE
HIGH	T_4	T_5	T_6	T_7 T_8 T_9 T_1 T_2 T_3	NONE

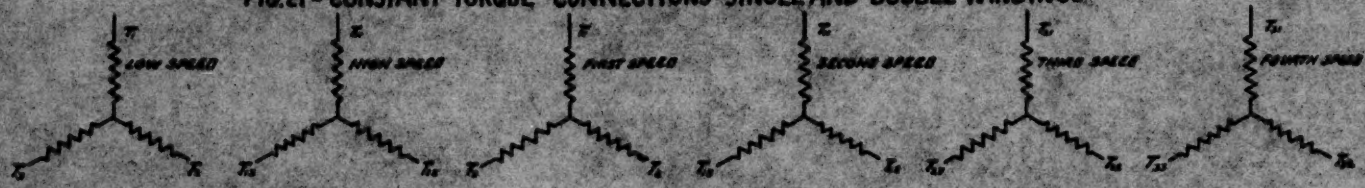
RELATIVE			
	TORQUE	H.P.	SPEED
LOW	1	1	1
2ND	2	2	2
HIGH	3	3	3

FOUR SPEED DOUBLE WINDING

SPEED	L_1	L_2	L_3		
LOW	T_1	T_2	T_3	OPEN	T_4 T_5 T_6 TOGETHER
2ND	T_7	T_8	T_9	T_1 T_2 T_3 T_4 T_5 T_6	T_{10} T_{11} T_{12}
3RD	T_4	T_5	T_6	T_7 T_8 T_9 T_{10} T_{11} T_{12}	NONE
4TH	T_{10}	T_{11}	T_{12}	T_1 T_2 T_3 T_4 T_5 T_6 T_7 T_8 T_9	NONE

RELATIVE			
	TORQUE	H.P.	SPEED
LOW	1	1	1
2ND	2	2	2
3RD	3	3	3
4TH	4	4	4

FIG.21 - CONSTANT TORQUE CONNECTIONS - SINGLE AND DOUBLE WINDINGS



TWO SPEED SEPARATE WINDINGS

SPEED	L_1	L_2	L_3	
LOW	T_1	T_2	T_3	T_4 T_5 T_6 OPEN
HIGH	T_7	T_8	T_9	T_1 T_2 T_3 OPEN

RELATIVE			
	TORQUE	H.P.	SPEED
LOW	1	1	1
HIGH	1	2	2

FOUR SPEED SEPARATE WINDINGS

SPEED	L_1	L_2	L_3	
1ST	T_1	T_2	T_3	ALL OTHERS OPEN
2ND	T_4	T_5	T_6	"
3RD	T_7	T_8	T_9	"
4TH	T_{10}	T_{11}	T_{12}	"

RELATIVE			
	TORQUE	H.P.	SPEED
1ST	1	1	1
2ND	1	2	2
3RD	1	3	3
4TH	1	4	4

19); (*c*) *constant horsepower motors* for use on lathes and other machine tools (see Figure 20). These, together with the *separate winding, constant torque motors,* in which each winding covers a standard pole grouping (see Figure 21), show the great flexibility of squirrel-cage induction motors. Plate H shows a line-start switch for multi-speed motors. It will be noted in the foregoing classes of double, and separate winding types of squirrel-cage induction motors, that if a casualty, such as a burn-out or ground happens in a coil or section of a coil, the motor is not rendered inoperative on the remaining speed combinations.

STARTING THE SQUIRREL-CAGE INDUCTION MOTOR.

Before proceeding to the next type of A.C. motor, the basic methods of *starting* the foregoing classes of *three-phase induction* motors will be briefly described. In general, the *squirrel-cage,* single-speed motor is started directly across the power line. One form of starter is shown in Plate E. Where the plant conditions limit the direct line start, or where reduced motor starting *torque* is required, *reduced voltage* start is offered and is accomplished by one of four methods. The most usual method is by the use of an auto-transformer (see Plate F).

THE AUTO-TRANSFORMER START. METHOD I.

An auto-transformer is defined as a transformer so connected that part of the load current is supplied by the primary current, and part by the secondary current. This is sometimes called a *compensator.* Figure 22 shows a diagrammatic sketch of a single-phase transformer connected as an auto-transformer. To illustrate the instantaneous current and voltage distribution, it has been assumed that the line volts is 100; the line start current 50 amperes; the desired starting current 30 amperes. These conditions would require a 100 to 60 ratio winding. The line current then becomes 18 amperes and the motor applied starting voltage becomes 60. Neglecting transformer losses, the apparent power in the line is 100 V. $\times$ 18 A. = 1800 V.A. and in the motor circuit it is 60 V. $\times$ 30 A. = 1800 V.A. This is to be compared with 100 V. $\times$ 50 A. = 5000 V.A. for direct line start. The relative

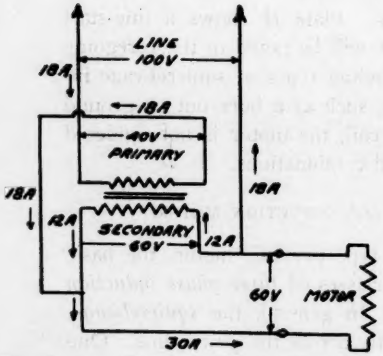


FIGURE 22.—SINGLE TRANSFORMER CONNECTED AS A SINGLE-PHASE AUTO-TRANSFORMER.

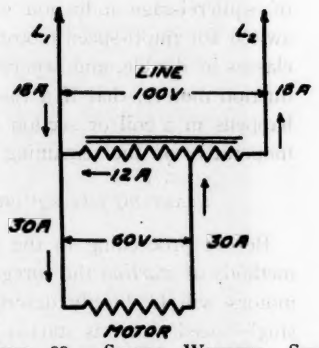


FIGURE 23.—SINGLE WINDING, SINGLE-PHASE, AUTO-TRANSFORMER.

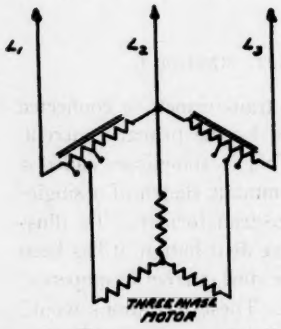


FIGURE 24.—THREE-PHASE, AUTO-TRANSFORMER WITH VOLTAGE TAPS.

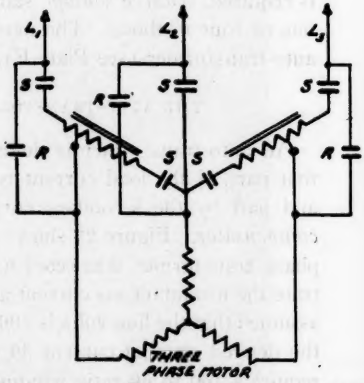


FIGURE 25.—THREE-PHASE AUTO-TRANSFORMER STARTING AND RUNNING CONNECTIONS.

amount of current or voltage supplied by the primary and secondary depends on the ratio of transformation. The current is approximately inversely proportional and the voltage is proportional to the number of turns in their respective windings. In present practice, the primary and secondary type, auto-transformer, has been simplified into the *one* winding type, with optional taps to obtain several values of reduced voltages. This form of auto-transformer is shown in Figure 23. The basic principles of operation are the same as in Figure 22. For three-phase motors, the scheme shown in Figure 24 is extended to show the application of two identical auto-transformers connected to supply reduced voltage to the three phases of the motor stator winding. Figure 25 still further extends the scheme to show the connections marked S, required for the *start* of the motor at reduced voltage, and the *running* connections at full line voltage, marked R.

THE Y — Δ LINE START FOR SQUIRREL-CAGE INDUCTION MOTORS. METHOD 2.

The second method of starting squirrel-cage induction motor, is known as starting Y, running Δ. This method which formerly had considerable application, is not used to any great extent commercially at the present day, but the possibilities are such that its application to naval services are of interest. A recent delivery of a Navy-type, motor-driven welding set, successfully uses it. This method assumes that the motor horsepower rating is designed on the basis of Δ connected primary. By external reconnection to the Y hook-up as shown in Figure 26, the motor may be line started with reduced voltage on the individual primary coils in the proportions of 100 to 57.7 (the vectorial voltage relation between Y and Δ).

In the application of the Y — Δ start, six main current leads are required from the motor, and suitable switches for the start and running connections, completes the installation. The method using the auto-transformer also requires switches but only three leads from the motor. For close connected installations, the Y — Δ start is advantageous as it eliminates the use of the auto-transformer with its insulated winding and appreciable relative weight. The Y — Δ

start, however, is confined to one value of voltage reduction, whereas with the auto-transformer, several taps are available in case the load is such that additional starting torque is required. For many types of service as for centrifugal fans, motor-generators, etc., the 57.7 per cent start of the Y — Δ connection is sufficient.

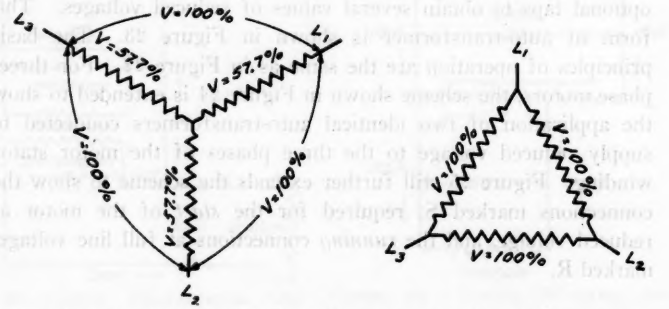


FIGURE 26—RELATIVE PHASE VOLTAGE FOR Y START Δ RUNNING, INDUCTION MOTOR.

Recent commercial practice indicates that most designs of induction motors are based on running Y connected, in which case, the Y start — Δ running scheme, can not be applied. The reason for using Y connected motors is stated to be on account of what is known as the "slot factor." This means that less coil insulation is required for the Y winding on account of less turns per phase winding, compared with the Δ winding. Therefore, larger wire and greater output may be obtained by using the Y winding, without increasing the slot sizes. Also in commercial designs, it has been recent practice to split the coils of each phase, and bring out nine lead-in wires for connection in combination so that a double voltage rating may be obtained (see Figure 27). This scheme defeats the possibility of using the Y — Δ start due to the impracticable number of lead-in wires, but serves to reduce the number of stock motors. Such motors are equally applicable to 110-220 volt or 220-440 volt systems at full rated horsepower, by merely reconnecting the external wires so that the split coils of each phase are in series for the higher voltage, or in parallel for the lower voltage rating.

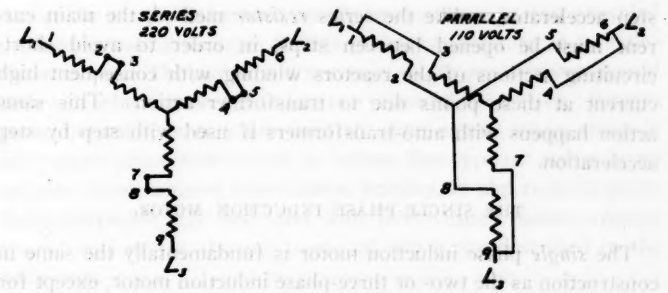


FIGURE 27.—Y CONNECTED INDUCTION MOTOR SHOWING EXTERNAL CONNECTIONS FOR TWO LINE VOLTAGE RATINGS.

THE SERIES RESISTOR START OF THE SQUIRREL-CAGE INDUCTION MOTOR. METHOD 3.

The *third* method of reduced voltage starting of squirrel-cage induction motors, is by the use of resistors in the primary circuit of each of the phases or in two of the phases. These resistors have no magnetic cores and the voltage drop caused by the usual I^2R loss, serves to reduce the voltage applied to the terminals of the primary or stator windings, much the same as with a D.C. motor where similar resistance is inserted in the armature circuit. The starting resistance is cut out in desirable steps without opening the circuit, as the motor accelerates. Although this system is not as economical in current drawn from the line as the auto-transformer, there is some saving in weight due to the absence of heavy magnetic cores required by the auto-transformer.

THE SERIES REACTOR START OF THE SQUIRREL-CAGE INDUCTION MOTOR. METHOD 4.

The *fourth* method of reduced voltage starting of squirrel-cage induction motors, is by the use of reactors in the primary circuit where *reactance* drop in voltage is obtained, in general, similar in action on the motor as in the case of the series resistance method. Although the reactor method is somewhat more economical in *power* drawn from the line, because of the fact that reactors require magnetic cores to obtain reactance, the weight is not appreciably different from the auto-transformer. In the use of step by

step accelerator, unlike the series *resistor* method, the main current must be opened between steps, in order to avoid short-circuiting sections of the reactors winding with consequent high current at these points due to transformer action. This same action happens with auto-transformers if used with step by step acceleration.

THE SINGLE-PHASE INDUCTION MOTOR.

The *single* phase induction motor is fundamentally the same in construction as the two- or three-phase induction motor, except for the important difference that single-phase current, if applied to the stator winding in a similar manner as for polyphase current, would have no starting torque. This is shown in Figure 28 where the magnetic flux builds up in one direction to maximum, dies down, and builds up again in the *opposite* direction, with each reversal of the single alternating current.

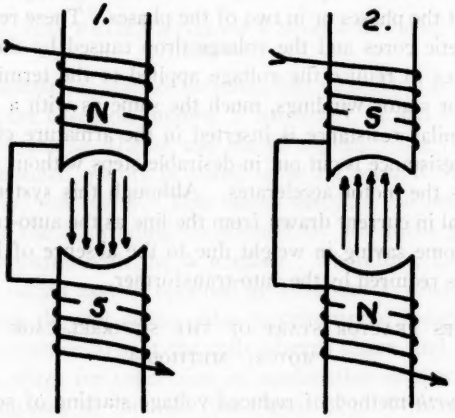


FIGURE 28.—SINGLE-PHASE MAGNETIC FLUX, REVERSING BUT NON-ROTATING.

It is evident in Figure 28, that the necessary rotating flux is not produced and no *starting* torque is available. However, it is well known that when a two-phase or three-phase induction motor having a low resistance rotor is running, and the line connection to

one of the phases is broken, the motor continues to run provided the load is not too heavy. In this case it is operating as a single-phase motor. The motor will not start, however (without special devices), when connected to but one phase of the supply. Single-phase induction motors are used to some extent where there is only single-phase distribution or where this type of motor in its simplest form, without commutator, brushes, or slip rings, is peculiarly adaptable, *e.g.* desk and wall fans. Such motors require special devices for starting, some of which are described in the following:

STARTING THE SINGLE-PHASE INDUCTION MOTOR.

A revolving field is necessary in order to make a single-phase induction motor self-starting. This is accomplished in several ingenius ways. One system known as the *split phase* type uses two separate windings on the stator, electrically displaced from each other similar to a *two-phase* winding. In one of the windings, termed the auxiliary winding, some inductance or capacity is included so that the phase displacement is either larger or smaller than in the other winding. This produces an elliptical revolving field which is an imperfect imitation of the uniform two-phase revolving field, but serves the purpose on this type of motor. When the motor has reached considerable speed, the auxiliary winding is open circuited by a hand switch or, automatically, by a centrifugal switch. The motor continues to run as a single-phase motor on one winding. The principle which causes the motor to operate after it is started in either direction is different from that of the polyphase induction motor which has a readily explained resultant rotating magnetic field in a definite direction. The explanation of the single-phase motor is quite involved and may be briefly stated as being a differential between a forward and backward rotating harmonic magnetic field. With the motor at rest, the differential is zero. When running, the differential builds up in the direction of rotation of the motor. The torque of a single-phase induction motor is not uniform as is the case of the two or three-phase motor, but pulsates from zero to maximum with each alternation of the current.

Another system of obtaining the phase displacement necessary to produce the revolving field is used on fractional horsepower motors and consists of a short-circuited copper ring on alternated magnetic poles of the stator. These are known as *shading* coils, the effect of which, by the current induced in them, is to retard the building up of the magnetic flux at these alternate points in the stator field system. This effect is out of phase with the other poles and thus serves to produce an imperfect revolving field in imitation of the two-phase principle.

All types of single-phase induction motors inherently have poor starting torque characteristics due to the imperfect revolving fields. This leads us to a class of single-phase motors which possess considerable starting torque but at the expense of a wound rotor, commutator and brushes similar to that of a D.C. motor.

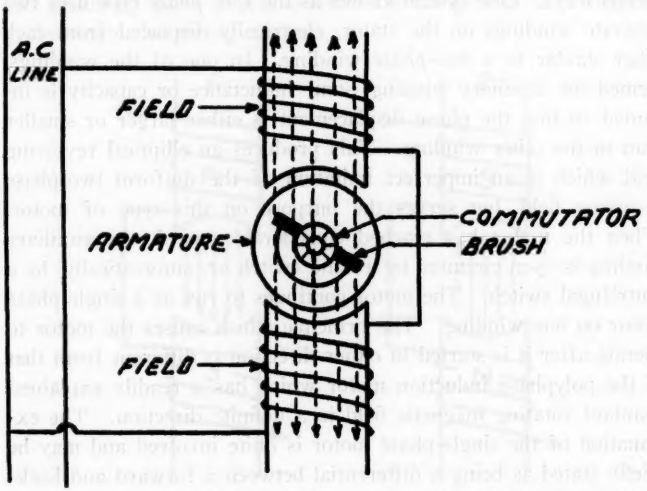


FIGURE 29.—SINGLE-PHASE REPULSION MOTOR.

Referring to Figure 29, this motor is shown with a stationary field winding connected to the line and produces a pulsating field as shown by the arrows. The armature or rotor is shown with the one set of brushes on the commutator short circuited, but at an

angle to the direction of the magnetic flux. The pulsating field induces secondary currents in the armature, and the latter tends to move into such a position as to be subjected to the minimum induction. This is impossible, because the direction of the magnetic axis of the armature is determined by the position of the brushes. Therefore, the armature revolves continuously in its effort to come into a stable position. Reversed rotation is obtained by shifting the brushes to the opposite side of the neutral axis.

THE REPULSION MOTOR.

The type of motor described above is called the *repulsion motor*. They are seldom used on account of difficulties in commutation, and their so-called *series* characteristics. The speed of the motor greatly increases as the load decreases, being in this respect similar to a direct-current series-wound motor. However, the repulsion *principle* is made use of in a class of useful motors known as *repulsion* start, *single-phase, induction* motors.

REPULSION START, SINGLE-PHASE INDUCTION MOTORS.

This class of motor uses the repulsion principle for starting, this being more effective for single-phase induction motors than the "split"-phase or the shading-coil methods, but with the disadvantage of the wound rotor, commutator, and brushes. The objection to poor commutation, inherent in the repulsion motor, is overcome by automatically short-circuiting the commutator when a certain speed is reached, and in some designs by also raising the brushes by a centrifugal device, to avoid unnecessary friction and wear. The motor then continues to run as a single-phase induction motor with a short-circuited secondary equivalent to the squirrel-cage rotor. This class of motors has some objections in certain applications where unexpected heavy overloads are experienced. Overload tends to reduce the speed of the rotor to the point where the centrifugal devices bring the commutator and brushes into action again with the result that the overload burns out the commutator and usually the armature windings.

SINGLE-PHASE, SERIES COMMUTATOR MOTORS.

The so-called *series* commutator motor covers a class of widely used motors which apparently meets the requirements for many power-driven domestic and office equipments such as vacuum cleaners, blowers, adding machines, etc., and for portable electric tools such as drills, hammers, grinders, etc. The motor requirements for the above applications are, good starting torque, one direction of rotation regardless of line polarity, and ability to operate on direct current. This latter requirement establishes the so-called *universal* current motor which operates, if used at speeds of from 4000 to 12,000 R.P.M., equally well on direct current or 60-cycle alternating current. In certain railway systems this class of motor is used in large sizes for locomotive propulsion.

The explanation of the operation of a series A.C. motor is exactly similar to that of the series D.C. motor. In the latter type of motor the armature, or rotor, consists of the usual insulated main current windings, commutator and brushes set at the electrical neutral point. The poles of the magnetic frame or stator surrounding the armature are energized by the main line current in series with the armature. The rotor revolves by repulsion of magnetic forces acting between the field coil flux and the flux produced by the current circulating in the armature coils. Reversing the direction of the current in both the armature and field, by changing the D.C. line connection, does not reverse the rotation of the rotor for the reason that the magnetic *relation* of the repulsion forces still remain the same. Reversed rotation can only be obtained by reversing the connections of either the series field or the armature, but not both. This fact, therefore, indicates that if alternating current is applied to the D.C. series motor, rotation of the armature in a definite direction will result. This direction of rotation can be changed only by inverting the connection between the field winding and the armature as is the case with D.C. In order to avoid excessive eddy-currents when A.C. is applied, the field and armature cores are required to be laminated. Also in the use of A.C., the electric and magnetic circuits are designed to keep self-inductive reactance down to reasonable limits, and the field winding and armature winding should have approximately equal

resistance and inductance. The foregoing special features show why the usual design of a series D.C. motor will not operate satisfactorily on A.C. On the other hand, the special features of the series A.C. motor do not preclude its use on D.C.

THE COMPENSATED SERIES COMMUTATOR MOTOR.

As indicated in the previous paragraph on the plain series commutator motor, the inductance of the field and armature windings when used with A.C. is of such value as to cause the current to lag greatly behind the voltage, with resultant very low power factor. The inductance of the field winding is reduced to a reasonable amount by employing few turns, low magnetic densities and

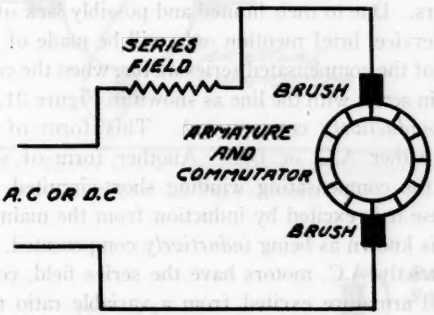


FIGURE 30—PLAIN SERIES COMMUTATOR MOTOR, A.C. OR D.C.

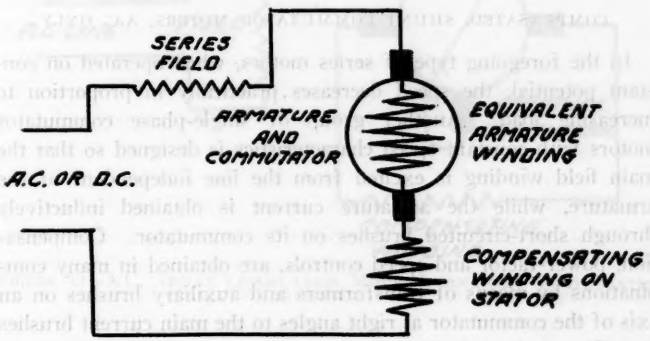


FIGURE 31—COMPENSATED SERIES COMMUTATOR MOTOR, A.C. OR D.C.

small air-gaps. For the armature, it is necessary to employ an auxiliary opposition winding on the stator, the number of ampere-turns and the location of which with respect to the current in the armature coils, serves to greatly neutralize the inductance of the armature winding. This is known as the *compensated* motor. When used with the *series* motor it is known as the *compensated series* motor. Figures 30 and 31 show the circuit diagrams of the plain series, and the compensated series motors.

COMPENSATED, SERIES COMMUTATOR MOTORS, A.C. ONLY.

There are numerous other types of series single-phase commutator motors other than the simple series and the compensated series motors. Due to their limited and possibly lack of application to Naval Service, brief mention only will be made of these types. In the case of the compensated series motor, when the compensating winding is in series with the line as shown in Figure 31, it is known as being *conductively* compensated. This form of motor will operate on either A.C. or D.C. Another form of strictly A.C. motor has the compensating winding short-circuited upon itself, in which case it is excited by induction from the main field winding. This is known as being *inductively* compensated. Still other forms of strictly A.C. motors have the series field, compensating winding and armature excited from a variable ratio transformer to accomplish speed control.

COMPENSATED, SHUNT COMMUTATOR MOTORS, A.C. ONLY

In the foregoing type of series motors, when operated on constant potential, the speed decreases practically in proportion to increasing load. Another group of single-phase commutator motors with constant speed characteristics is designed so that the main field winding is excited from the line independent of the armature, while the armature current is obtained inductively through short-circuited brushes on its commutator. Compensation, power-factor and speed controls, are obtained in many combinations by means of transformers and auxiliary brushes on an axis of the commutator at right angles to the main current brushes (see Figures 32 and 33).

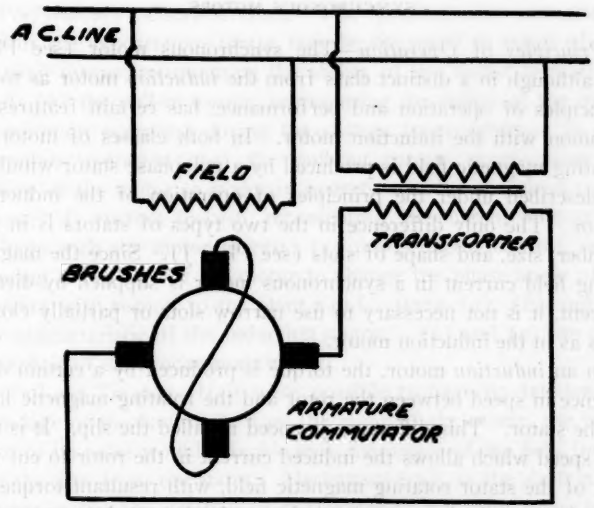


FIGURE 32—A.C. SHUNT COMMUTATOR MOTOR CONDUCTIVELY COMPENSATED USING A TRANSFORMER.

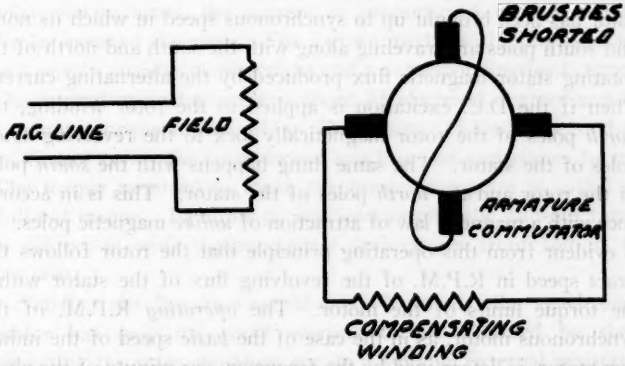


FIGURE 33—A.C. SHUNT COMMUTATOR MOTOR INDUCTIVELY COMPENSATED.

SYNCHRONOUS MOTORS.

Principles of *Operation*—The synchronous motor (see Plate I), although in a distinct class from the *induction* motor as to its principles of operation and performance, has certain features in common with the induction motor. In both classes of motors a rotating magnetic field is produced by a polyphase stator winding, as described under the principles of operation of the induction motor. The only difference in the two types of stators is in the number, size, and shape of slots (see Plate J). Since the magnetizing field current in a synchronous motor is supplied by direct-current, it is not necessary to use narrow slots or partially closed slots as in the induction motor.

In an *induction* motor, the torque is produced by a certain difference in speed between the rotor and the rotating magnetic field of the stator. This difference in speed is called the slip. It is the slip speed which allows the induced current in the rotor to cut the flux of the stator rotating magnetic field, with resultant torque in accordance with electro-magnetic laws. In the *synchronous* motor the rotor consists of an assembly of alternate north and south electro-magnetic poles, energized by continuous direct-current supplied from an external source. Assume first that the unexcited rotor has been brought up to synchronous speed in which its north and south poles are traveling along with the south and north of the rotating stator magnetic flux produced by the alternating current. Then if the D.C. excitation is applied to the rotor winding, the *north* poles of the rotor magnetically lock to the revolving *south* poles of the stator. The same thing happens with the *south* poles of the rotor and the *north* poles of the stator. This is in accordance with a magnetic law of attraction of *unlike* magnetic poles. It is evident from this operating principle that the rotor follows the *exact* speed in R.P.M. of the revolving flux of the stator within the torque limits of the motor. The *operating* R.P.M. of the synchronous motor, as in the case of the *basic* speed of the induction motor, is determined by the frequency per minute of the alternating current, divided by the number of pairs of poles of the rotor (or stator).

Performance Characteristics.—The performance characteristics of the synchronous motor may be discussed in terms of (*a*) starting torque, representing the ability of the motor to start the load; (*b*) the pull-in torque, representing the ability of the motor to maintain operation during the change from induction to synchronous operation; (*c*) the pull-out torque, representing the ability of the motor to maintain operation under peak-load conditions; (*d*) current in-rush, representing the current flow at line voltage with the motor at rest; (*e*) power-factor control, representing the ability of the motor to change the phase angle of the current with respect to the plant e.m.f. Items (*a*), (*b*) and (*d*) are characteristic of the induction motor. (*c*) and (*e*) are characteristic of the synchronous motor.

Pull-out Torque.—If it were possible to have no friction and windage or mechanical load on the rotor of the motor, the center line of its poles would coincide with the center of the field formed by the flux from the stator. Mechanical load on the shaft of the motor causes the position of the center of the rotor poles to *lag* behind the center of the poles formed by the rotating field of the stator. This difference, called the *angle of lag* of the rotor, causes current to be drawn from the line. If the motor is operating at unity power-factor, the current is proportional to this *angular displacement* of the rotor. For a given mechanical load, there will be a certain angular displacement and a corresponding load current. The normal operating angle is about 35 electrical degrees and the maximum torque angle is about 65 degrees. If loaded beyond the maximum point, the rotor looses synchronism and comes to rest. The torque required to cause the breakdown point is called the *pull-out* torque. In terms of full load torque, the pull-out torque is subject to wide design control and ranges from 150 to 400 per cent.

Starting the Synchronous Motor.—Normally, the synchronous motor has only the small starting torque obtained by short-circuiting the rotor windings across a suitable external resistance. In this starting arrangement, the rotor field winding functions as a wound-rotor *induction* motor. Torque is obtained up to a rotor speed 8 to 15 per cent below synchronism. In order to obtain *additional* starting torque, an auxiliary winding is placed on the

D.C. rotor. This winding, in the form of an induction motor squirrel-cage, consists of a number of high resistance bars pushed through partially closed slots in the rotor pole-heads, parallel to the shaft, and brazed to copper connecting rings at each end (see Plate K). This winding is known as a *damper* or *amortisseur* winding and serves not only to produce induction motor starting torque, but to damp out oscillations of the rotor about its normal position due to pulsation in the load when running at synchronous speed. In some installations a flywheel is used to further dampen load oscillations (see Plate L). By design variations in the resistances of the damper winding and the external field resistors, starting torques of 50 to 200 per cent full load torque may be obtained. This combination start is practically equivalent to that of the *double* squirrel-cage induction motor.

Pull-in Torque.—It is evident from a study of the *induction* motor characteristics, that operating under this principle, the motor will accelerate only to a speed just short of synchronous speed. The exact settling point will vary according to the design and the load carried by the rotor shaft. Due to the limited heat capacity of the damper winding, the motor can not be operated continuously on this starting winding. After the damper winding and the field winding have served their purpose in starting the motor and bringing it to nearly synchronous speed, the field winding is switched to D.C. excitation. Synchronizing force is then exerted on the rotor which speeds ahead to bring its north and south poles into coincidence with the revolving magnetic flux poles of the stator. The ability of the machine to develop a suitable induction-motor torque at about 95 per cent synchronous speed is called the *pull-in torque*. It is expressed in terms of per cent of full-load torque and ranges, depending on design, from 35 to 125 per cent. After the rotor has *pulled-in* to synchronism with the revolving flux of the stator, it continues in synchronism until forced out by a shaft load beyond the torque limit of the motor. Due to the fact that the D.C. field of the rotor is revolving at the same R.P.M. as the stator A.C. field, the damper winding, which is also revolving at the same speed, cuts no magnetic flux and therefore induced current, present during starting, becomes zero except when oscillations caused by

load changes are set up in the rotor. Figure 34 shows the typical curve values of starting torques of the two rotor windings, the resultant torque and the pull-in point.

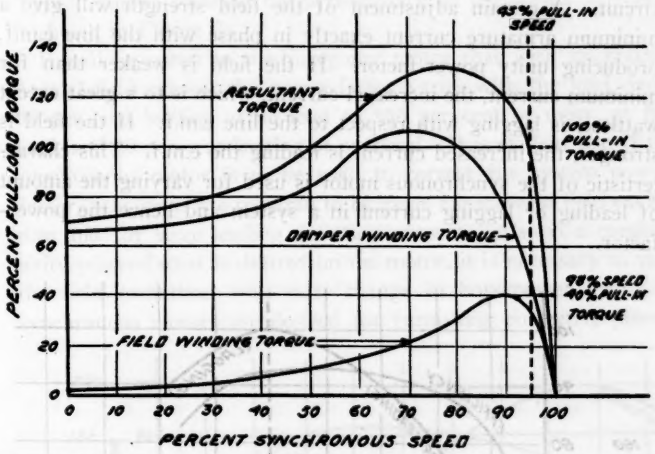


FIGURE 34.—SYNCHRONOUS MOTOR INDUCTION STARTING TORQUE CURVES SHOWING PULL-IN VALUES.

Current In-rush.—In the start of the synchronous motor, the current in-rush as to be expected, is of the same high magnitude as that of the induction motor. In order to reduce the value to reasonable limits, auto-transformer reduced voltage or series reactance coils may be employed in the primary or power circuit. In either case, full line voltage is applied to the motor prior to applying the D.C. field to the rotor, so that maximum torque will be available before shifting to synchronism. As the starting torque from the short-circuited rotor field winding is not of high order, the motor may be started using the damper winding only. However, the in-rush current will be increased and the open circuited induced voltage of the D.C. field winding, if not used at the start, will be of high order, ranging from 5000 to 35,000 volts, depending on the size and design of motor.

Power-factor Control.—An important operating characteristic of a synchronous motor is its ability to correct power-factor by supplying to the circuit to which it is connected the magnetizing

current required by induction apparatus on that circuit. It is well known that a synchronous motor can have its armature current varied in magnitude and phase by varying the current in the field circuit. A certain adjustment of the field strength will give a minimum armature current exactly in phase with the line e.m.f. producing unity power-factor. If the field is weaker than for minimum current, the increased current, which is to a great extent wattless, is lagging with respect to the line e.m.f. If the field is stronger, the increased current is leading the e.m.f. This charactertistic of the synchronous motor is used for varying the amount of leading or lagging current in a system and hence the power-factor.

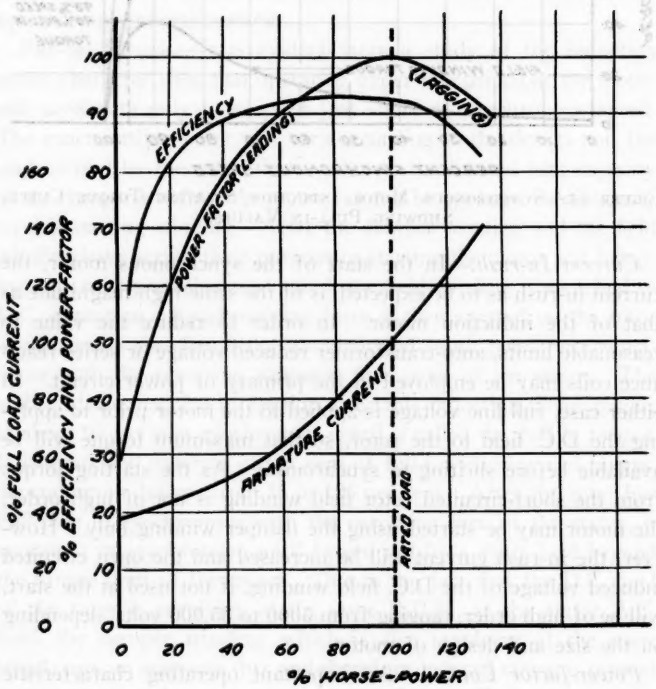


FIGURE 35—PERFORMANCE CHARACTERISTICS OF A UNITY POWER-FACTOR SYNCHRONOUS MOTOR.

The Unity Power-factor Motor.—The unity power-factor motor with about 50 per cent starting, 40 per cent pull-in and 150 per cent pull-out torque, is the most economical synchronous motor. Typical curves showing the performance of the design of motor is shown in Figure 35.

It will be noted in the foregoing motor that with maintained normal field current the power-factor varies with the load, from 90 per cent leading at no load to 100 per cent or unity, at full load, and 20 per cent lagging at overload. It is evident that if the synchronous motor is to be used to correct for system power-factor, provisions are required to be made for increase field excitation and for large leading armature current. Also if a constant unity power-factor is desired on the motor, it is necessary to vary the field excitation with each change in horsepower load. If synchronous motors are desired for furnishing corrective power-

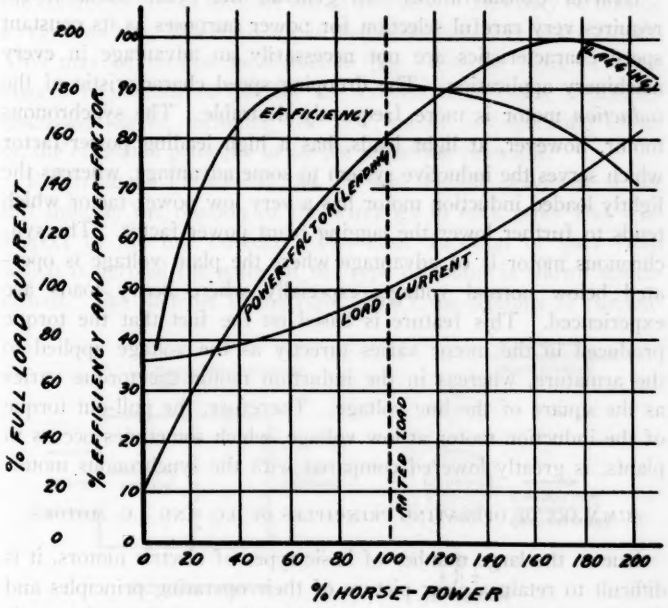


FIGURE 36.—PERFORMANCE CHARACTERISTICS OF AN 80 PER CENT POWER-FACTOR (LEADING), SYNCHRONOUS MOTOR.

factor as well as for power, recourse is made to designs which will produce additional armature and field currents without overheating.

The 80 Per Cent Leading Power-factor Motor.—This class of synchronous motor is designed to be operated at 80 per cent leading power-factor at full horsepower output. In order to accomplish this feature the weight and size is correspondingly greater than for the unity power-factor motor. The characteristic performance curves of this motor are shown in Figure 36.

In every installation where the synchronous motor is required for power-factor correction, it is necessary to select the motor the current rating of which is suitable to not only furnish its own power output, but to circulate the reactive current to the system which will compensate for the normal lagging current produced by induction plant loads.

General Considerations.—In general, the synchronous motor requires very careful selection for power purposes as its constant speed characteristics are not necessarily an advantage in every machinery application. The drooping speed characteristic of the *induction* motor is more frequently desirable. The synchronous motor, however, at light loads, has a high leading power-factor which serves the inductive system to some advantage, whereas the lightly loaded induction motor has a very low power-factor which tends to further lower the lagging plant power-factor. The synchronous motor is of advantage where the plant voltage is operated below normal voltage, especially where heavy loads are experienced. This feature is based on the fact that the torque produced in the motor varies directly as the voltage applied to the armature, whereas in the induction motor the torque varies as the square of the line voltage. Therefore, the pull-out torque of the induction motor at low voltage, which sometimes occurs in plants, is greatly lowered compared with the synchronous motor.

SUMMARY OF OPERATING PRINCIPLES OF D.C. AND A.C. MOTORS.

Due to the large number of basic types of electric motors, it is difficult to retain a clear picture of their operating principles and fundamental differences. This is especially so where each type is discussed separately in more or less detail, and also for the reason

that the accepted terms used to name the basic types are not descriptive on a common basis. For example, the term *induction* motor is derived on the basis of the generation of a secondary current by *induction;* the term *series commutator* motor is derived on the basis of the *series* relation in the circuit of a stationary and revolving windings, and the employment of a *commutator*; the term *synchronous* motor is derived on the basis of the *speed* relation between the rotor and the alternating current of the stator, etc. It just so happens that *all* types of electric motors operate on one or two of three basic electro-magnetic laws.

The first law is that a conductor carrying current is surrounded with a concentric magnetic field the polarity of which is dependent on the direction of current in the conductor. The second law which embodies the first law is that a conductor carrying current, if located in a magnetic field of some other source not parallel to the conductor, tends to move out of this field. This may be termed a *repulsion* law. The third law is that *unlike* magnetic poles *attract.* This may be termed an *attraction* law. On the basis of these laws it is possible to classify the various basic types of motors discussed herein, including the D.C. motor, as operating either on the *repulsion* principle or on the *attraction* principle.

Referring to Figures 37, 38, 39 and 40, the diagrams at the left indicate the relation of the windings to each other and with respect to the line current. The basic function or part from which is derived the name of the type of motor is shown underscored. The sketches to the right show cross-sections of current-

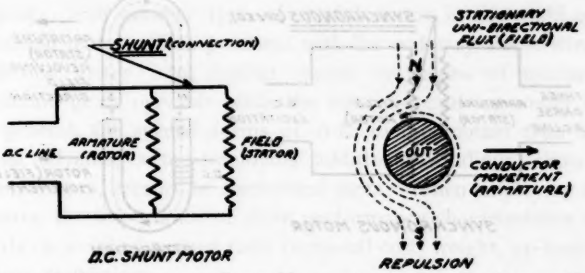


FIGURE 37—THE DIRECT-CURRENT SHUNT MOTOR, SCHEMATIC AND OPERATING PRINCIPLES.

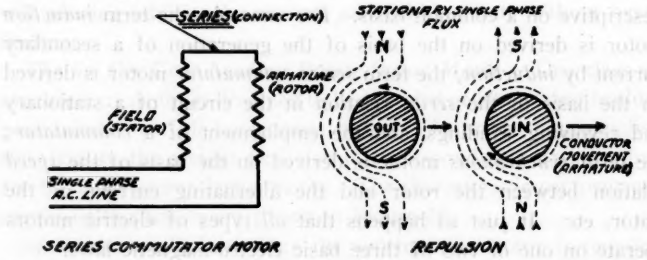


FIGURE 38.—THE A.C. (OR D.C.) SERIES COMMUTATOR MOTOR SCHEMATIC AND OPERATING PRINCIPLES.

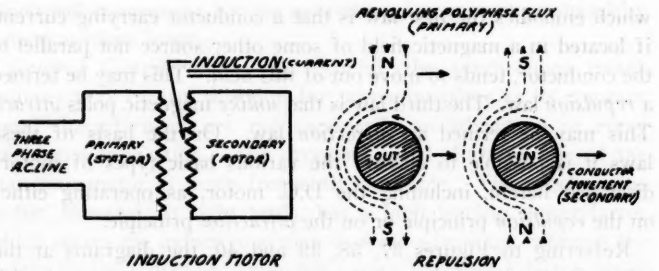


FIGURE 39.—THE INDUCTION MOTOR SCHEMATIC AND OPERATING PRINCIPLES.

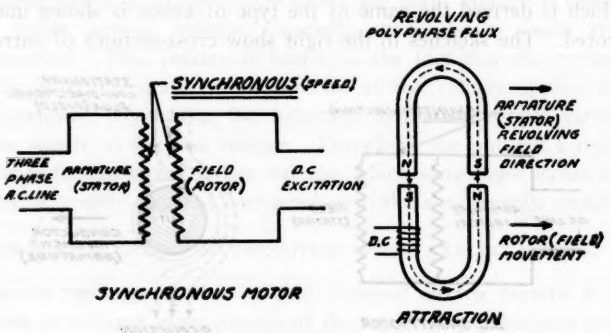


FIGURE 40.—THE SYNCHRONOUS MOTOR SCHEMATIC AND OPERATING PRINCIPLES.

carrying conductors in magnetic fields and cross-sections of magnetic poles. The flux directions are shown in dotted lines. The electro-magnetic principles which cause the movement of the conductor (rotor) are indicated as repulsion or attraction in the direction of the solid arrows. In an actual motor this movement would result in the rotation of the moving element of the motor.

CONCLUSION.

The various types of A.C. motor described in this article by no means exhaust the present day types offered by commercial engineering developments. The types described, however, cover the basic classifications of the ordinary general service motors manufactured on a competitive basis, which in general should be adequate for various applications to Naval Service.

Many special and ingenious forms of single and polyphase A.C. motors have been invented and designed for the specific purpose of either overcoming the inherent shortcomings of the basic types, or to further extend their speed range and speed control. Among the special motors is one designated as a *self-excited synchronous induction* motor. This motor is designed to greatly improve the low power-factor of the induction motor but uses induction motor starting and overload advantages. At light load and full load it has the speed and power-factor advantages and characteristics of the synchronous motor. Another special group of motors is known as the *brush shifting* type. These motors have constant speed characteristics with numerous speed ranges, obtained by mechanically shifting the angular position of a commutator brush rigging. Still another type of special motor is the multi-speed induction motor, which produces with the ordinary single winding induction motor four distinct speeds by means of mechanical reduction gears operable while the rotor is revolving under load. In general, the special forms of A.C. motors obtain their additional advantages by employing additional windings, slip-rings, commutators, brushes or mechanical parts. When employing these motors, the importance of their performance characteristics must needs be weighed against their increased cost, weight, up-keep and patent restrictions.

NOTE: This is the second of three articles on Alternating Current Motors and Generators; the third covers Generators.

TRANSLATION.

THE APPLICATION OF THE HYDROGEN BRAZING METHOD TO THE MANUFACTURE OF INTERNAL COMBUSTION ENGINES.

By Fr. Sass, AEG, Berlin.

The method of connecting steel parts by welding them with copper in a hydrogen atmosphere was used for the first time by the General Electric Co., Schenectady, N. Y., and was applied to the manufacture of refrigerators and other apparatus. The Allgemeine Elektricitäts Gesellschaft (German General Electric Co.), Berlin, which has friendly relations with the above-mentioned company, has taken over the method and has used it in the manufacture of Diesel engines in the making of cylinder covers, pistons, and other important parts, with the result that particularly advantageous types have been created which have considerably increased the reliability and life of these parts.

An alloy of copper, nickel and zinc, with a melting point of approximately 1150 degrees C. is used as the welding material. The additions of nickel and zinc have the purpose of making the melted welding material somewhat stronger and somewhat thicker when in the liquid state, as it has been shown that pure copper in the molten state is so extremely thin-liquid that it not only penetrates very readily into the narrowest joints, but at times even runs through these joints without adhering to the inside, if the joints at some points happen to be just a little wider. The latter cannot always be avoided in the case of heavy and large parts, such as cylinder covers with a diameter of several feet, notwithstanding the greatest precision in the production. The addition of nickel and zinc has given an effective remedy against this failing.

The hydrogen atmosphere in which this brazing process takes place, acts as a de-oxidation means; by means of its reducing

action, it removes possibly existing layers of oxide, both from the brazing material and also from the parts to be welded, and protects the parts from oxidation even during the brazing process and the subsequent period of cooling. After the brazing, the parts are consequently entirely free of scale, which is particularly advantageous in those parts which later come in contact with the fuel (see Figures 16 and 17); in addition, the parts are automatically annealed by the brazing process, so that the objects such as cylinder covers, leave the furnace entirely free of internal stresses.

The construction of such a furnace is shown in Figure 1. The bottom and the sides consist of sheet steel, dressed with fireproof brick. The arched cover is also made in the same manner. The seal between the cover and the sides is established in the most simple manner by welding a wide annular groove of sheet steel to the outside of the upper part of the sides; this groove is filled with

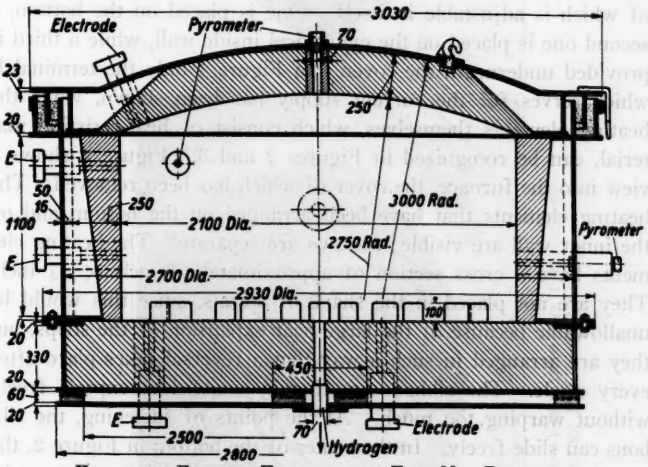


FIGURE 1.—ELECTRIC FURNACE OF 6 FEET NET DIAMETER.

dry cement powder. The cover is pressed into this groove when it is placed on top of the furnace after the parts that are to be welded are placed within; the cover has a sharp edge and the weight is sufficient to insure an air-tight seal between the cover and the sides. Before connecting the electric current, it is neces-

sary to remove all the air from the inside of the furnace. For this purpose, a hydrogen line is connected to the highest point of the cover, and the hydrogen gas flows into the furnace at a pressure which is kept constant at approximately 8 inches water column; the hydrogen, being lighter than air, will at first accumulate underneath the cover. The air will be forced out through a hole provided in the center of the bottom and is gradually removed entirely from the inside of the furnace. If the parts that are to be brazed have hollow spaces which is, for instance, the case in most cylinder covers for Diesel engines, then it is necessary to make provisions whereby the air is given an opportunity to escape from these hollow spaces so that oxy-hydrogen gas cannot be formed at any point. The electric current should not be closed until pure hydrogen gas escapes from the pipe line connected to the opening in the bottom of the furnace.

The furnace shown in Figure 1 has three separate circuits, each of which is adjustable in itself. One is placed on the bottom, a second one is placed on the cylindrical inside wall, while a third is provided underneath the cover. In Figure 1 only the terminal E which serves for the current supply has been shown, while the heating elements themselves, which consist of heat-resisting material, can be recognized in Figures 2 and 3. Figure 2 shows a view into the furnace, the cover of which has been removed. The heating elements that have been arranged on the bottom and on the inner wall are visible; the two are separate. The heating elements have a cross section of approximately 1 inch $\times$ ¼ inch. They are not placed in the shape of spirals, since this would be unallowable because of the large heat expansion of the strips, but they are arranged in such a way that a reversal takes place after every circle. The ribbons are thereby enabled to expand freely without warping too much. At the points of fastening, the ribbons can slide freely. In the center of the bottom in Figure 2, the opening for the outlet of the air or of the hydrogen gas can be plainly seen. Figure 3 shows the cover, viewed from the bottom; the heating ribbon is arranged in the same manner as that on the bottom.

In this furnace the electric power is supplied at 220 volts while the current for this size of furnace is approximately 700 to 800

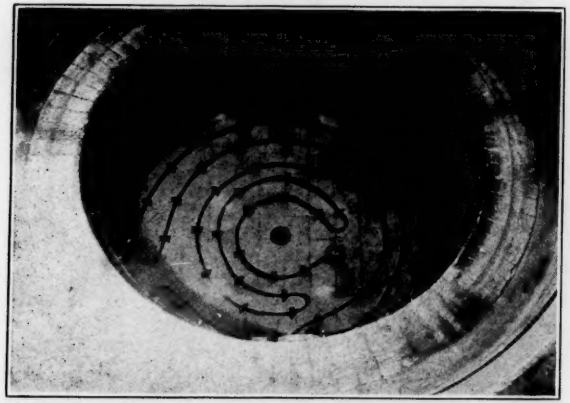


FIGURE 2.—VIEW INTO THE FURNACE OF FIGURE 1; COVER REMOVED.

FIGURE 3.—BOTTOM VIEW OF THE COVER.

FIGURE 4.—BRAZED JOINT, MAGNIFIED (MAGNIFICATION APPROXIMATELY 100 TIMES).

amperes. The three circuits are regulated during the entire welding process in such a way that the pyrometers which are arranged at various points of the furnace (see Figure 1) indicate temperatures that are as uniform as possible. The pressure of the hydrogen gas is continuously held at the same pressure (8 inches of water) and the hydrogen supply is not interrupted until the temperature, during the cooling period, has dropped to 200 degrees C. At that temperature there is no longer any danger that the remaining hydrogen will be ignited when air is added, since the ignition temperature of hydrogen lies considerably higher. The furnace can then be opened and the welded object can be taken out.

If a welded joint is investigated micrographically, the illustration in Figure 4 is obtained. It shows that a certain percentage of copper is diffused in the edge zones of the iron because of the chemical relation between the elements iron and copper, while inversely about the same percentage of iron has entered into the thin layer of brazing material.

The mutual alloying results in a brazed connection of exceptionally high unit strength, and the total strength of any joint can be controlled by designing with suitable contact area. With proper construction the joints can thus be made as strong as the body metal.

A few *applications* of this brazing metal to the manufacture of important elements of internal-combustion engines will now be described.

Figure 5 shows the manner in which the *cylinder cover of four-cycle Diesel engines* can be designed according to the hydrogen brazing method. The upper part A of the illustration shows the cover in the position in which it is brazed, namely, with the plate b of forged steel, which comes in contact with the fire, *on top;* the part B of the illustration shows the cover in the normal position in the machine after it has been finished. The cover consists mainly of the cast-steel body a, and of the steel plate b, which are brazed together in the hydrogen atmosphere. Since the cast-steel body a, is cast without the plate b, it is open on one side (Figure 6); The cores are therefore readily accessible and the core sand can be removed easily and rapidly after the casting, which is a requirement in the case of steel castings which, as known, shrink

greatly upon cooling. In order to produce a strong and tight connection between the plate b, and the openings for the different valves, the threaded bushings c, d, e, are provided which press the plate b, and the cast-steel body a, solidly together; these bushings are also brazed to the part. The brazing material is placed in the slots f, in the shape of pieces of wire of sufficient length, and the cover is then placed in the furnace. It takes approxi-

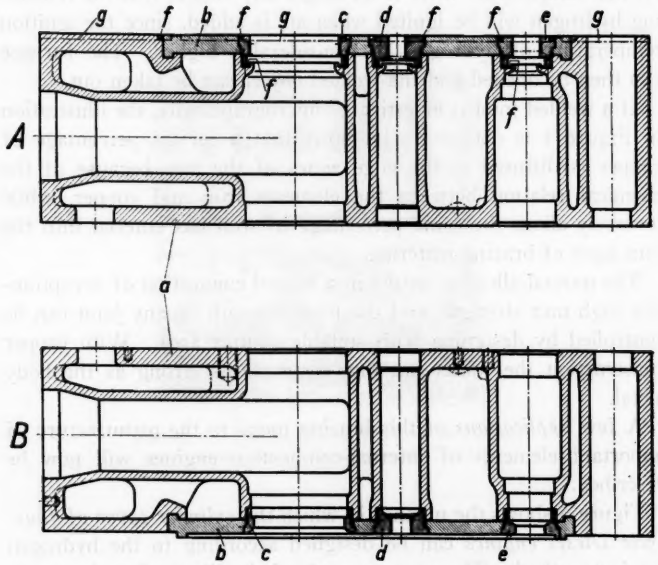


FIGURE 5.—CYLINDER COVER FOR 4-CYCLE DIESEL ENGINES.
A = Cover in Reverse Position for Brazing.
B = Cover, Finished, in the Proper Position.

a = Cast-steel Body.
b = Plate of Forged Steel.
c = Threaded Bushing for Suction Valve.
d, e = Threaded Bushings for Fuel and Starting Valves.
f = Slots for Brazing Material.
g = Contour of the Finished Cover.

mately 8 to 9 hours to heat the furnace up; the melting temperature of the brazing material is then reached; the brazing material is melted and penetrates into all the joints whereby a very strong connection is produced. It suffices to keep the furnace at the maximum temperature of approximately 1200 degrees C. for a

quarter of an hour only; the current is then interrupted and the furnace is left alone for the purpose of cooling. The cooling takes approximately 40 hours; the cover can then be removed and finished in the normal manner. On that side which later faces the combustion space in the motor, the cover is turned down according to the line g, indicated by dots and dashes. Part b of Figure 5 shows the cover in the finished state.

In Figure 6 all parts which are required for a four-cycle cover are shown: the cast-steel body, the forged-steel plate, the threaded bushings c, d, e, (Figure 5) for the five valves and a roll of brazing wire which is cut into small pieces. In Figure 7, the steel plate has been put in place and one of the threaded bushings has been screwed in; the other four are still lacking. It is evident that the assembly of such a cover is rather simple and does not require many parts.

The advantage of this construction lies in the fact that a much stronger and more reliable design is obtained by the connection of cast steel and forged steel than would be possible in the otherwise usual method which uses cast iron. Although forged steel is less favorable than cast iron with respect to heat stresses or thermal stresses because of its higher modulus of elasticity, this is again compensated by the fact that the forged steel plate can be made thinner than a plate of cast iron, because of its greater strength, so that the heat stresses are decreased as a result of the more intensive cooling. In addition, forged steel is of course much superior to cast iron, as it is never assured in the case of cast iron that there are no porous places or holes which would reduce the strength of the cover to unallowable extent.

The very stable design of such covers is particularly advantageous in the case of *two-cycle engines,* the cylinder covers of which are subjected to higher stresses than those of four-cycle engines because of the more rapid succession of ignitions. On the *lower* side of double-acting two-cycle engines there is the additional factor that the construction is somewhat more complicated than at the upper side, as it is necessary, as a rule, to provide several supply points for the fuel because of the piston rod, and further, as it is necessary to arrange one opening for the starting valve and one for the safety valve. Figure 8 shows the manner in which such

a cover can be manufactured in the brazed construction without great difficulties. The bottom b, made of forged steel, is pressed into the cast-steel body a, with a strong collar. The opening c, which is cast in and which is split into two parts, serves as a place for the starting valve and also for the safety valve; it is connected to the steel plate by means of the threaded bushing d. The indicator bore e, also terminates in the opening c. Four tubes f, arranged at 90 degrees, serve for the insertion of the fuel supply lines. The tubes f, are threaded into the cast-steel body a, and are solidly brazed thereto. The nut g, has the purpose of preventing the thin liquid brazing material from running out at the lower end of f. After the cover has cooled off, the four nuts g, are milled off and the steel plate b, is turned down according to the dotted contour line.

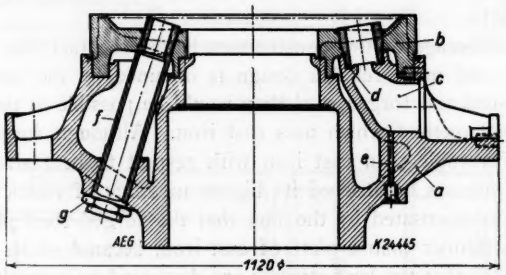


FIGURE 8.—BRAZED LOWER CYLINDER COVER FOR DOUBLE-ACTING TWO-CYCLE ENGINES.

a = Cast-steel Body.
b = Plate of Forged Steel.
c = Opening for Starting Valve and Safety Valve.
d = Threaded Bushing.
e = Indicator Bore.
f = Tube for Fuel Supply.
g = Nut (for Brazing Only).

Figure 9 shows the cast-steel body of the above-described cylinder cover; the forged steel plate has been removed. The favorable accessibility of the cores of the steel casting is clearly visible in the illustration.

After the cover has been brazed and finished and after the tubes with the nozzles have been inserted, the cover is ready for assembly (Figure 10). Four fuel nozzles are provided, each of which has one nozzle bore only, out of which the fuel is sprayed in an approximately tangential direction, however, in such a way that the spray

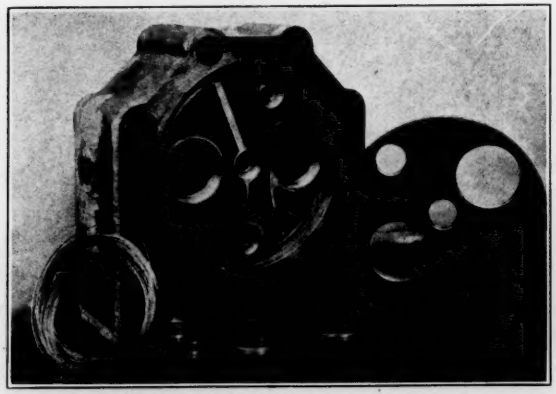


FIGURE 6.—INDIVIDUAL PARTS OF A 4-CYCLE CYLINDER COVER.

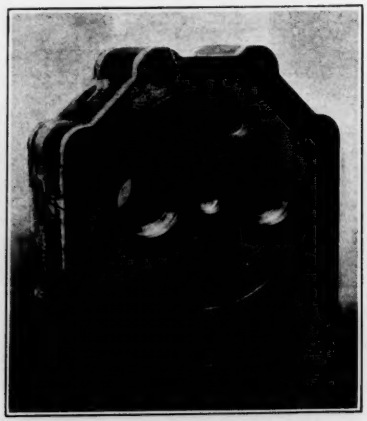


FIGURE 7.—CYLINDER COVER FOR A 4-CYCLE ENGINE WITH STEEL PLATE INSERTED. BEFORE THE BRAZING.

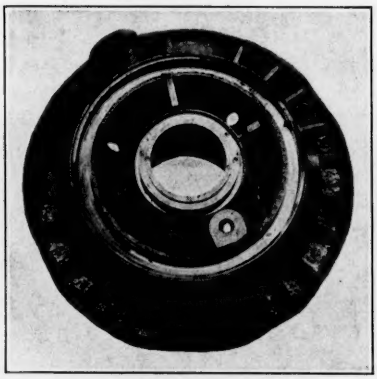


FIGURE 9.—CAST-STEEL BODY FOR THE CYLINDER COVER OF FIGURE 8.

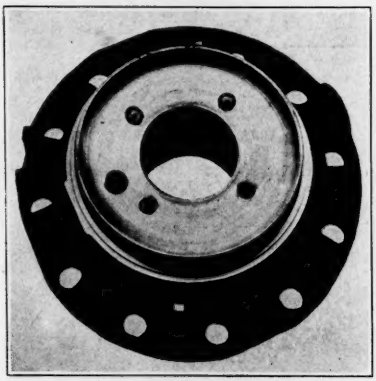


FIGURE 10.—LOWER CYLINDER COVER OF A DOUBLE-ACTING TWO-CYCLE MOTOR WITHOUT COMPRESSOR, READY TO BE ASSEMBLED.

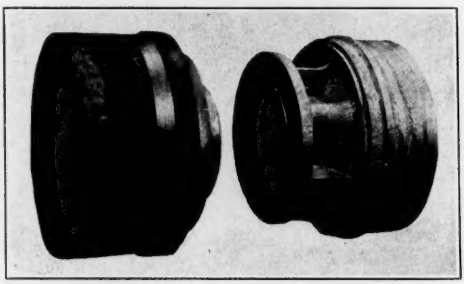


FIGURE 15.—BRAZED PISTON HEAD.
Left: Upper Head; Right: Lower Head.

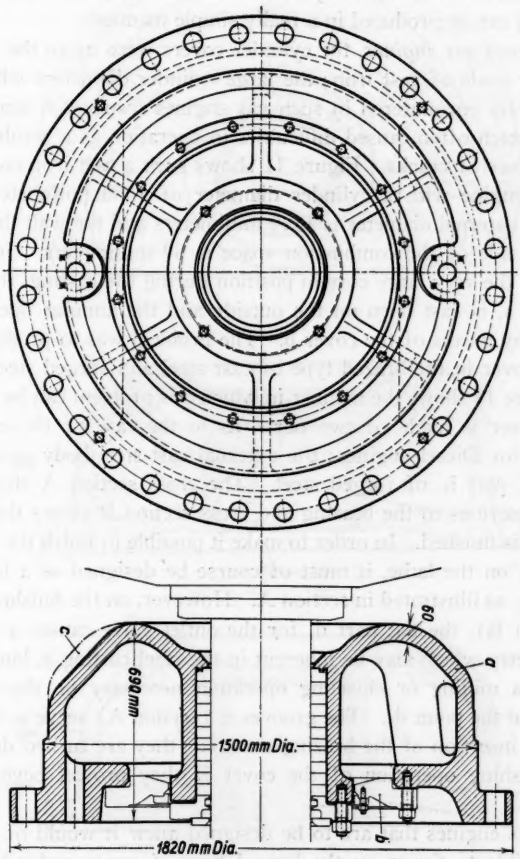


FIGURE 11.—CAST-IRON CYLINDER COVER OF A LARGE GAS ENGINE.

a = Main Body of Cast Iron.
b = Cover for the Cooling-water Space.
c = Pocket for the Outlet Valve.

will not strike the adjacent nozzle. The opening on the left side of the illustration is for the starting and safety valves. The Figure also shows that the lower cylinder cover of double-acting two-cycle engines can be produced in a really simple manner.

In large gas engines, the cylinder covers were up to the present usually made of cast iron; the large cylinder diameters which are frequently encountered in such gas engines resulted in large castings, which often caused difficulties in operation as a result of the occurrence of cracks. Figure 11 shows such a cast-iron cover for a gas engine with a cylinder diameter of 1500 millimeters; the largest external diameter is 1820 millimeters and the wall thickness on the side of the combustion space is 60 millimeters. In order to keep the very large core in position during the casting, the main casting a, is cast open on the outside and the annular opening is closed by means of the cover b. The problem was to produce this large cover in the brazed type of cast steel and forged steel.

Figure 12 shows the manner in which this problem can be solved. The cover is made of two parts, as in the case of the cylinder covers for Diesel engines: the external cast-steel body a, and the internal part b, of forged steel. The cross section A shows the cover previous to the brazing and cross section B shows the cover after it is finished. In order to make it possible to finish the forged piece b, on the lathe, it must of course be designed as a body of rotation, as illustrated in section A. However, on the finished piece (section B), the flat part d, for the outlet valve causes a certain asymmetry which may be inherent in the steel casting a, but which makes a milling or chiseling operation necessary on the forged part b, at the point d_1. The grooves c, (section A) serve as before, for the insertion of the brazing material; they are turned down in the finishing operation of the cover if they project beyond the grooves.

In gas engines that are to be designed anew it would of course be possible to figure on the brazed type of cover and select the shape in such a way that the forged part b, obtains a form that can readily be manufactured. In the described case, however, an existing cover (Figure 11) had to be replaced so that the shape was given and could not be changed.

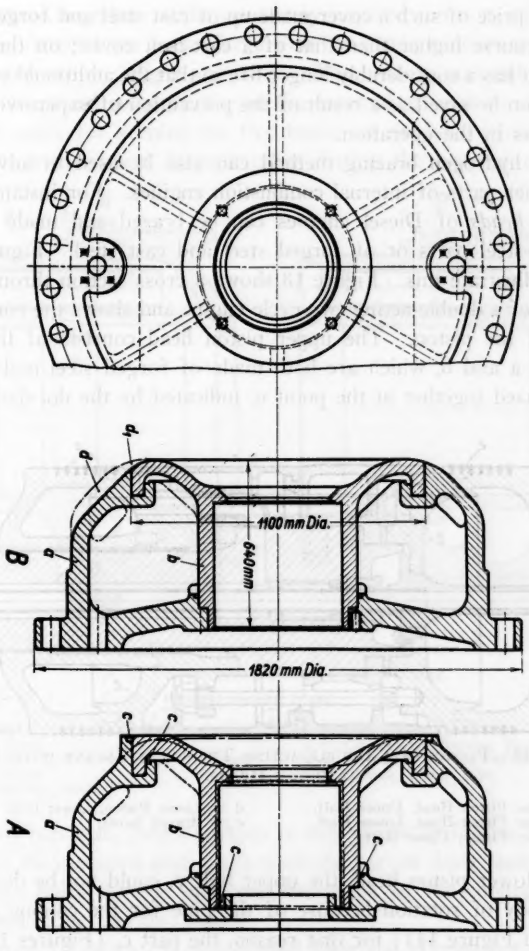


FIGURE 12.—CYLINDER COVER OF A LARGE GAS ENGINE, BRAZED OF CAST STEEL AND FORGED STEEL.

A = Cover Before the Brazing.
B = Finished Cover.

a = Cast-steel Body.
b = Part of Forged Steel.
c = Grooves for Brazing Material.
d, d_1 = Pocket for Outlet Valve.

The price of such a cover made up of cast steel and forged steel is of course higher than that of a cast-iron cover; on the other hand, it has a considerably longer life so that the additional expense will soon be saved as a result of the prevention of expensive interruptions in the operation.

The hydrogen brazing method can also be used to advantage for other parts of internal combustion engines. For instance, the *piston heads* of Diesel engines can be brazed and made up of forged-steel parts or of forged steel and cast steel. Figures 13 to 15 illustrate this. Figure 13 shows a cross section through the piston of a double-acting two-cycle engine and shows the construction of the piston. The upper piston head consists of the two halves, a and b, which are both made of forged steel and which are brazed together at the point e, indicated by the dot-dash line.

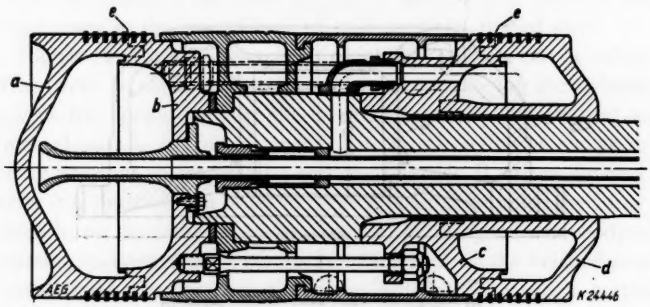


FIGURE 13.—PISTON OF A DOUBLE-ACTING TWO-CYCLE ENGINE WITH BRAZED PISTON HEADS.

a = Upper Piston Head, Upper Half.
b = Upper Piston Head, Lower Half.
c = Lower Piston, Upper Half.
d = Lower Piston, Lower Half.
e = Brazed Joints.

In the lower piston head, the upper half c, could not be designed as a body of rotation because of the pipe for the cooling water (h, i, in Figure 14); for that reason, the part c, (Figures 13 and 14) has been made of cast steel while the corresponding part d, is forged of steel. The manufacture of a lower piston head is shown more clearly in Figure 14 where cross section A shows the condition prior to the brazing, and cross section B shows the finished piston head. The cast-steel part c, and the forged part d,

are pressed together in the accurately finished joints e, after the brazing material has been placed into the inside grooves g, which afterward are no longer accessible. The brazing material can of course be placed subsequently on the external grooves g. Several pins f, serve for keeping the two halves of the head in the same position with respect to each other during the brazing process.

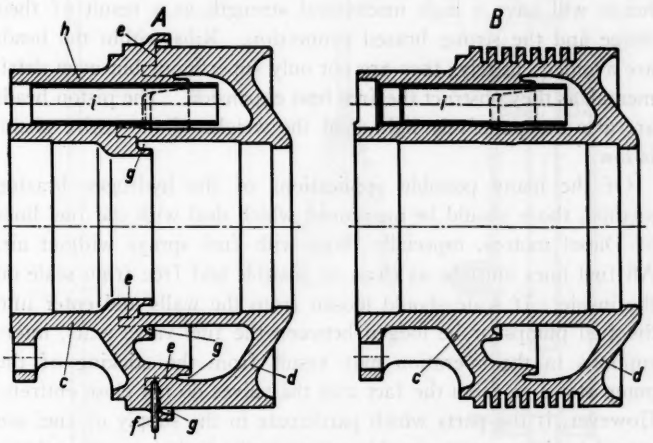


FIGURE 14.—MANUFACTURE OF A LOWER PISTON HEAD.
A = Piston Head Prior to the Brazing.
B = Finished Piston Head.

c = Upper Half of the Head, of Cast Steel.
d = Lower Half of the Head of Forged Steel.
e = Brazing Joints.
f = Pins.
g = Grooves for Brazing Material.
h = Extension for Cooling Water Inlet.
i = Cooling Water Pipe.

At two points h, (one of which is also visible in Figure 15), the ribs of the cast-steel part c, are made thicker; at those points, there are two holes for the inlet and the outlet of the cooling water. The steel tube i, is also brazed.

Figure 15 shows the piston head after the brazing but prior to the finishing. Only the external brazing grooves have been turned down. In this condition, the heads are subjected to an internal water-pressure test of 850 pounds per square inch; in this manner it is assured that the brazing is completely tight at all points. The heads can then be finished on the outside and the slots for the

piston rings can then be provided. Finally, the entire piston is assembled with the piston rod in the manner shown in Figure 13.

The advantage of this construction is the same as that for cylinder covers; it is possible to use thin forged steel on the sides of the piston that come in contact with the hot gasses; the forged-steel element makes a good cooling possible whereby the piston heads will have a high mechanical strength as a result of their shape and the strong brazed connection. Ribs within the heads are avoided entirely; they are not only superfluous but even detrimental, as they obstruct the free heat expansion. The piston heads are also comparatively light, and the weight of the entire piston is low.

Of the many possible applications of the hydrogen brazing method, those should be mentioned which deal with the fuel lines of Diesel motors, especially those with fuel sprays without air. All fuel lines must be as clean as possible and free from scale on the inside. If scale should loosen from the walls and enter into the fuel pumps or be lodged between the fuel valve seats, interruptions in the operation may result from the sticking of the pump stems or from the fact that the valves do not close entirely. However, if the parts which participate in the supply of fuel are brazed to the greatest possible extent in the hydrogen atmosphere, the formation of scale will be positively prevented by the reducing action of the hydrogen gas, and the parts of the pipe line will leave the furnace in an absolutely clean condition. The AEG uses the brazing process for the fuel suction line and its parts which are shown in Figure 16a; they are brazed in an electric hydrogen furnace. The parts a, (air tank), b, (suction line) and c, (flange), which are shown in heavy lines in Figure 16a, are brazed together forming one piece. This piece is screwed to the fuel pump block d, by means of the flange c; one air tank a, is provided for each of the pump stems. In that manner no oscillations of the oil columns can be propagated from the fuel pump into the main supply line e.

In smaller Diesel engines in which the pressure line between the fuel pump and the inlet valve is short, the entire tube f, with the connections g and h, can be brazed in the electric furnace. In order to obtain a positive fastening, the elements g and h are screwed on the end of the pipe with fine threads. In that manner

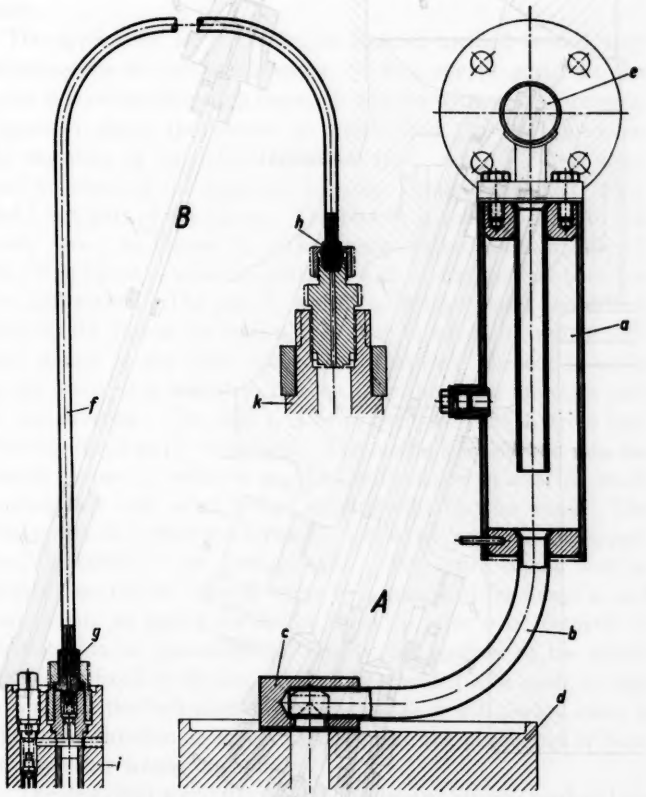


FIGURE 16.—PARTS OF THE SUCTION LINE A AND OF THE PRESSURE LINE B OF DIESEL ENGINES WITHOUT COMPRESSORS, BRAZED IN HYDROGEN.

a = Suction Air Tank.
b = Part of the Suction Line.
c = Flange.
d = Fuel Pump Block.
e = Main Suction Line.
f = Pressure Tube.
g, h = Brazed Connection.
i = Fuel Pump.
k = Fuel Supply Valve.

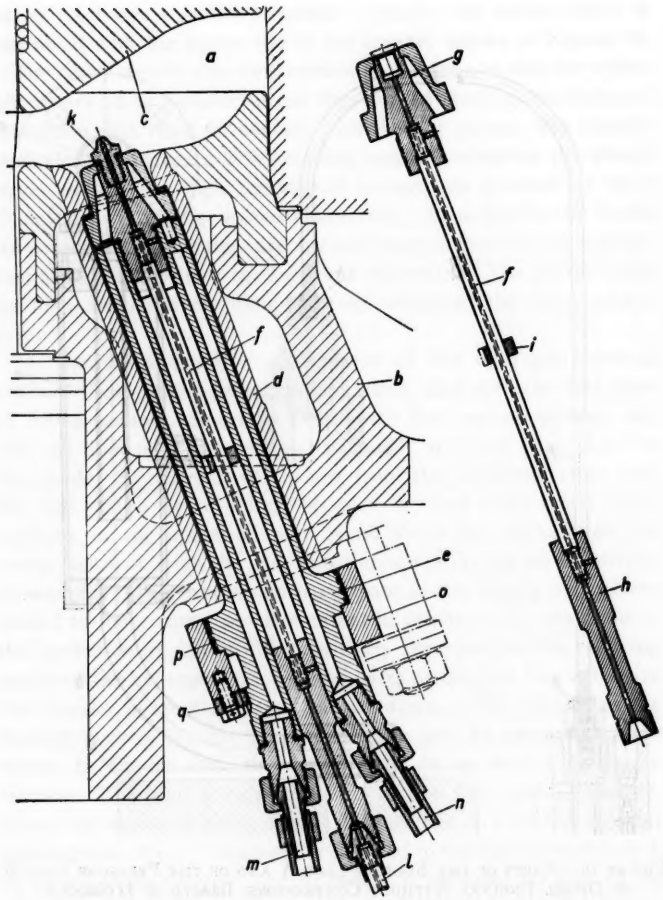


FIGURE 17.—FUEL SUPPLY LINE FOR THE LOWER SIDE OF DOUBLE-ACTING TWO-CYCLE MOTORS WITHOUT COMPRESSORS.

a = Lower Combustion Space.
b = Lower Cylinder Cover.
c = Piston.
d = Brazed Pipe.
e = Steel Body.
f = Supply Pipe.
g = Nozzle Support.
h = Connector.
i = Support to prevents Vibrations.
k = Fuel Nozzle.
l = Supply Line for the Fuel.
m = Cooling Water Inlet.
n = Cooling Water Outlet.
o = Pressure Flange.
p = Thread Used for Removing e.
q = Element for Fixing the Direction of the Fuel Stream.

a fuel line is obtained between the pump i, and the supply valve k, which is entirely free of scale, both on the outside and on the inside.

The application of the hydrogen brazing method is also very advantageous in the manufacture of *fuel supply parts* on the lower side of double-acting two-cycle engines without compressors. Figure 17 shows the manner in which these parts are made in the machines of the AEG-Hesselman type. a is the lower combustion space of the machine, b is the (brazed) cylinder cover and c is a part of the piston. The pipe d, is solidly brazed to the cover (see f in Figure 8). The supply body consists mainly of the forged pipe e, which is provided with a large central bore for the fuel pipe f. The pipe f, which has a heavy wall and which supplies the fuel to the nozzle, is brazed on top to the nozzle support g, and at the lower end to the connection element h, while in the center it is brazed to the disc i, as shown on the right part of the drawing. The disc i, is to prevent the tube f, from performing unallowable vibrations. The nozzle k is screwed into the nozzle support g, which is provided with hollow spaces for water cooling and with small brazed guiding ribs for the water. The fuel enters at l, while the connections m and n serve for the supply and the outlet of the cooling water. The entire supply body is pressed against the cylinder cover b, by means of the flange o, and can readily be pulled out at the thread p after o is removed, in case it is to be disassembled. Finally, the position of the supply body e, is fixed by the key q, which is provided with teeth, in such a way that the fuel which leaves the nozzle k will always move in the same direction so that it cannot strike the piston rod or leave in any other wrong direction.

The described applications of the hydrogen-brazing method have partly been in operation for a period of five years on sea-going motor-boats; they have proved so successful that they have also been applied frequently in Diesel engines of foreign manufacture.

LUBRICATING OIL REVEALS ENGINE CONDITIONS.

By Lieutenant Ralph R. Gurley,* U. S. N., Member.

One of the important functions of the U. S. Naval Engineering Experiment Station at Annapolis, Maryland is the examination of lubricating oils to determine their suitability for use in the Naval service. Refiners who desire to bid for the Navy's business in this line submit samples of their products for test and make a deposit to defray the expense involved. This Station has been testing lubricating oils in this manner since 1908. The desirability of a definite order of merit for all oils submitted for test was early apparent but it was not until 1920 that definite progress was made in this field. At that time the " Work Factor" method of evaluating lubricating oils began to be formulated. By 1928 it was in definitely usable form, and in 1930 was first employed in making the award of the annual contract for the Navy's business.

The Work Factor evaluation of a lubricating oil involves a complete physical and chemical analysis of the oil before and after a 100-hour run in the Oil Endurance Testing Machine. This machine, of which there are six at the Station, consists primarly of a motor-driven steel journal revolving in a babbitted bearing so made that the cap pressure is adjustable. Five quarts of the oil to be tested are poured into the oil reservoir from which the oil is circulated through the bearing by a small gear pump. The oil is neither cooled nor heated during the test. After the journal is started the bearing cap pressure is adjusted to 150 pounds per square inch and the journal speeded up to 2000 R.P.M. The oil pressure is maintained at 10 pounds per square inch for light oils and 15 pounds per square inch for heavy oils. A continuous run of one hundred hours is made, no new oil being added during the test.

The changes that occur in the oil during the test are indicated by a comparison of the analyses made before and after the test and serve as the criterion of the stability of the oil. Changes in vis-

*U. S. Naval Engineering Experiment Station, Annapolis, Maryland.

cosity, neutralization number, and carbon residue are considered to be the most indicative of the oil's stability. For this reason, the changes that occur in these three facors are used in computing the "Work Factor" of the oil tested. An oil that suffers no change in these factors during the endurance test will receive a work factor of 1.0. As the resulting changes increase the work factor will fall below 1.0. The lowest acceptable figure is 0.60. The bid price per gallon divided by the work factor gives the "Service cost" per gallon. It is on this "service cost" that the contract is awarded, the lowest "service cost" receiving the contract.

Since the Navy has been buying its lubricating oils on the "work factor" and "service cost" basis, complaints from the Service have been few and far between. Considering the enormous number of applications for which these oils are used throughout the United States Navy, this is indeed significant. Such applications include reduction gears, turbine bearings, complete lubrication in aircraft, motor-boat, automobile and Diesel engines, and, in addition, steam cylinder lubrication. It would be unreasonable, in view of the severity of the service encountered in these types of machinery, not to expect that at least once in a while failures would be attributed to the lubricating oil. Therefore, it is not surprising that, occasionally, this Station receives reports that the oil "breaks down" or forms an "asphaltic sludge" in the crankcases of internal combustion engines.

These infrequent reports of unsatisfactory performance of lubricating oil delivered under Navy contracts receive careful investigation at this Station. Whenever practicable, a sample of the used oil or sludge deposit is obtained for analysis. In no uncertain terms this analysis reveals the engine conditions, mechanical or operational, which were responsible for the "break down" of the oil. Exceptional changes in viscosity, a marked rise in carbon residue, an unusual increase in acidity, the presence of iron oxides, gasoline or salt water, and a superabundance of oxidized oil, all tend to show that the oil has been used in an engine in poor mechanical condition, or not in proper adjustment, or that oil of the proper viscosity has not been employed.

Lubricating oils are not expected to counteract the mechanical deficiences of the engine. However, the effects of some undesir-

able engine conditions can be offset by the selection of an oil of the proper viscosity. For instance, the disadvantages of excessive piston clearances can be counteracted to a certain extent by the employment of an oil of higher viscosity than that recommended for a new motor. The same idea is involved in the use of higher viscosity oils in summer than in winter. For proper lubrication under widely varying conditions a liberal range of viscosities must be available. It is with this in mind that the Navy has developed its viscosity classification for lubricating oils which is given below. The corresponding S.A.E. numbers are noted for comparison.

		Viscosity Saybolt	
	Navy Symbol	*At 130° F.*	*At 210° F.*
S.A.E. No.	*No.*	(*Seconds*)	(*Seconds*)
10	2110	100-115	.....
20	2135	125-145	.....
30	2190	180-200	.....
40	2250	240-260	.....
50	3080	.....	75-85
....	3100	.....	90-100
60	3120	.....	115-125
70	3150	.....	140-160

It will be noted that the last three digits of the Navy symbol number of an oil indicate the average viscosity of the oil at the temperature of classification. Contractors making deliveries to Government activities use the Navy symbol method of classification, and when speaking of lubricating oils, Navy engineers also employ this method of identification.

In the above table the entire scale of viscosities for automotive lubrication is fairly well covered so that there is an oil for every ordinary operating condition, but, as pointed out above, there is no oil that will correct faults of engine operation or adjustment. Such faults are almost invariably the cause of unsatisfactory oil performance. The following paragraphs recount a few of this Station's experiences in the testing of used oils to determine the cause of purported breakdown of the oil in service. The examples described are typical.

The U. S. S. ....., when submitting oil samples for semi-annual check test, reported that the contract oils of symbols 2310,

3100 and 3120 were unsuitable for use in motor-boat engines because, "by reason of their asphalt base they left heavy residues in the crankcase," and, furthermore, broke down quickly, necessitating frequent change. At the same time, contract oil of symbol 2250 was reported to be satisfactory for Diesel engines.

Tests of the samples (of new oil) submitted by this Ship indicated that these oils had practically the same qualities as the oils for which the contract had been awarded. No samples of the used oils were forwarded. This Station suspected some mechanical or operating fault to be responsible for the difficulties listed by this ship because the symbol 2250 oil had been reported satisfactory for Diesels whereas the symbol 2310 was reported unsatisfactory for motor-boats. Both of these oils are made from the same base crude by the same process, hence, to quote the Station's reply, "since the tendency to oxidize and sludge is greater—in a Diesel engine than in a motor-boat engine, it is difficult to understand the cause of the unsatisfactory results obtained from the use of 2310 in motor-boat engines when 2250 is satisfactory for Diesels." Normally, sludging is the result of the oxidation or saturation of the unsaturated compounds in the new oil. High temperatures in contact with exhaust gases and air are instrumental in accelerating this oxidation. These conditions are far more aggravated in Diesels than in motor-boat engines.

The ship in question furthermore recommended that a paraffine base oil be substituted on the contract for motor-boat use. This recommendation was made on the assumption that an oil which was giving satisfactory service in the ship's boats was a paraffine base oil. It so happened that this oil was a blend of naphthene and paraffine base oils. So are the symbol 3100 and 3120 oils which were reported as unsuitable. Apparently, therefore, the base from which the oils were made could not be considered a factor in the difficulties experienced. As a matter of fact the contract symbol 3120 more nearly resembled a paraffine base oil than the oil reported as satisfactory.

Clues to the real source of this vessel's difficulties with the lubricating oil in her motor-boat engines were found in the analysis of the sludge deposit from the motor-boat crankcase. The analysis of this deposit follows:

	Per cent
Water	17.45
Lubricating Oil	68.52
Oxidized Oil	8.05
Free Carbon	4.72
Ash	1.71
Analysis of Ash	
Sodium Chloride	0.90
Iron Oxide	0.81

The Station's comments on this analysis are worth repeating verbatum: "The analysis of the sludge deposit shows the presence of large amounts of salt water and free carbon. Neither of these constituents is the result of (normal) lubricating oil depreciation. The salt water in the deposit, caused by contamination with sea water, was largely the cause of the excessive deposits because it emulsified with the lubricating oil to form a thick adhesive emulsion. Under normal operating conditions lubricating oil forms very little free carbon. The free carbon in crankcase oil or in crankcase deposits of gasoline engines is caused mainly by the escape of incompletely burned gases between the cylinder walls and the piston rings. The free carbon in the partially burned gases is absorbed by the lubricating oil and is deposited in the crankcase.

"The viscosity of (the symbol) 2310 oil used on the V-6 engine was unquestionably too low for the operating conditions of the engine, since it did not form a proper seal between the pistons and cylinder walls and thus allowed the escape of the exhaust gases into the crankcase. Moreover, the high percentage of iron oxide in the deposit shows that there was excessive wear of piston rings or cylinders resulting from rupture of the oil film between these parts."

The presence of the salt water in this sludge deposit was no doubt a surprise to the engineer officer of this vessel. It is at first difficult to conceive of the manner in which salt water could get into the crankcase. One explanation of this situation is that, when an engine equipped with a wet muffler back-fires, water is

very apt to get into the engine through the exhaust header and eventually find its way down into the crankcase. It is more likely, however, that the salt water entered through the clutch housing when the bilges were allowed to flood to that level. Carelessness in selecting the oil container when transferring the oil from ship to boat could also result in the contamination of the oil with salt water. The presence of the carbon particles in the oil in this case destroyed the oil's demulsifying ability and allowed the "asphaltic" sludge to form. The very best grade of paraffine base oil would react in much the same manner.

The solution in this case involves better engine adjustment, more frequent pumping of bilges, and substitution of a heavier lubricating oil. The selection of the proper viscosity oil for any engine is a problem that can be solved by the responsible engineer, and by him alone. Too light an oil will allow blow-by of exhaust gases, show excessive oil consumption and undue wear of pistons and cylinders; too heavy an oil will result in increased gasoline consumption and unnecessary lapping in of the pistons and cylinders, not to mention increased difficulty in starting. Oil of the proper viscosity is the lightest oil which will form and maintain, at operating temperatures, a lubricating film and complete oil seal around the pistons.

Another naval activity forwarded a sample of sludge deposit from the crankcase of a motor-boat, stating that considerable trouble had been encountered with plugged oil lines and burned out bearings. A sample of used oil submitted at the same time showed 23 per cent gasoline. The deposit analyzed as follows:

	Per cent
Lubricating Oil	66.31
Gasoline (dissolved in oil)	19.75
Water	5.00
Free Carbon	3.97
Asphaltic Matter	1.70
Long Fiber Asbestos	1.12
Salt (NaCl)	0.92
Oxide of Iron with trace of Copper	0.70
Sodium Sulphate	0.53

The long fiber asbestos was undoubtedly the cause of the plugged oil lines. Its presence in the crankcase can be attributed only to carelessness. In this analysis, we again recognize the free carbon and sulphates resulting from blow-by of exhaust gases, the salt and water from flooded bilges or gasket leakage, and the iron oxide from wear of piston rings and cylinder walls. Of all the items listed above only the asphaltic matter is the product of normal lubricating oil depreciation. The other products have entered through careless or inefficient operation of the engine.

The Experiment Station recently completed a series of service tests on all approved brands of symbol 3100 oil on the 225 H.P. Stirling gasoline engines of a Coast Guard patrol vessel. Every oil proved satisfactory and no sludge deposits like those described above were encountered. It is also interesting to note that the changes which took place in the oils during these tests were entirely comparable to the results obtained on the Oil Endurance Testing Machine.

The Navy Department is not the only government activity that buys its lubricating oils on Navy contracts. Among others, the Post Office Department, the Department of the Interior, and the War Department make use of these contracts for the purchase of lubricating oils for their services in the field. It is in the service of these government departments that the Navy contract oils find their greatest application to automobile use.

An agency of the Department of the Interior in the Southwest recently had occasion to complain about the performance of Navy lubricating oil. It appears that temperatures as low as —10 to —25 degrees F. were encountered and that, at these temperatures, it became necessary to tow the government cars to get them started for work in the mornings. This condition was blamed on the fact that the lubricating oil congealed in the crankcases. It was reported that after starting the oil soon thinned out so much as to be unfit to lubricate the engines. Considerable second gear driving was encountered.

To quote from the Experiment Station's reply: "There are no oils recommended for automotive use which will allow easy starting without dilution at —10 to —25 degrees F. and at the same time

give satisfactory lubrication at engine temperatures of 200 degrees F., which may be encountered in extended driving in second gear. Furthermore, * * * there is no gasoline on the market with which a car can be started at —10 degrees F. or lower when using the proper winter oil in the crankcase, provided there is no dilution of the oil. (The temperatures noted refer to the actual engine temperatures and not to surrounding atmospheric temperatures.) It stands to reason that long periods of standing in the weather will eventually bring engine temperatures down to atmosphere."

The problem of easy starting is one of the most widely discussed in the automotive field today. Solutions suggested include using larger batteries and using lighter oils in conjunction with an oil cooler. The following measures were suggested to this agency as offering a possible solution to the difficulties noted:

(*a*) Make every possible effort to prevent engines of the cars from being chilled below +10 degrees F. when starting is attempted.

(*b*) Use symbol 2135 oil in the ———— car at temperatures below zero degree F. (symbol 2190 had been used previously).

(*c*) Use high test gasoline during winter weather.

(*d*) Keep batteries fully charged. (They can give only 50 per cent capacity at —20 degrees F. anyway.)

(*e*) Do not race the engine when warming up. Give the oil film time to form on the cylinder walls.

It does not seem right, at first glance, to recommend a lighter oil when it is stated that the oil already thins out too fast in use. This recommendation was made with a view to lessening the starting difficulties and thus reducing the gasoline dilution due to unburned gasoline entering the crankcase at this stage. There was considerable dilution in the sample of used oil which accompanied the agency's complaint, and this was responsible for the quick thinning out of the oil as reported.

Subparagraph (*e*) above was included in the light of the fact that iron oxide was found in the ash of the used oil. The process of starting a gasoline engine in cold weather involves rupturing the cold oil film between the piston rings and the cylinder walls.

If the engine is immediately raced there is no lubricating film present to reduce the wear of the parts. The engine should be run at very light load and slow speed until the oil has had time to warm up and form a lubricating film at the operating temperature. This applies to motor-boat engines as well as automobile engines.

The experience of this agency calls attention to the fact that there are some conditions under which even the gasoline can not give the desired results. Just as the engine has its limit of power, so the oil and the gasoline have certain limits of usefulness and the expectancy of satisfactory operation must be confined to these limits. The nature of lubricating oil is such that an oil which will flow freely at —25 degrees F. will not have sufficient body at 200 degrees F. to form a lubricating film.

Another agency of the Department of the Interior in the Northwest reported rapid wear in automobile engines using Navy contract oils, and sent in a sample of used oil which gave the following analysis:

	Used Oil	*Normal Expectancy*
Neutralization number	3.03	0.10
Reaction	Acid	Neutral
Water, per cent	2.25	None
Gasoline, per cent	12.0	2.50
Carbon residue, per cent	0.65	0.24
Ash, per cent	0.95	0.10
Nature of ash	Iron Oxide	.....
Precipitation number	0.70	0.15
Precipitation number (using Benzol as diluent)	0.50	.....
Iron Sulphate	Present	.....

The values of the various factors found in the oil sample submitted for test are supplemented above by some average values which could be reasonably expected in a proper oil used for about two thousand miles in the average motor car in good condition. In the oil from the agency the high Neutralization Number and the Acid Reaction indicate that an inorganic acid has entered the

oil from some source. The presence of the water could be attributed to leakage from the cooling system or condensation in the crankcase of the moisture in exhaust gases which have blown by the pistons. The high percentage of gasoline present indicates that the curburetor needs adjustment, piston clearances are excessive, or that difficulties have been experienced in starting. Dilution caused by choking is generally overrated. Use of too light an oil would also account for some gasoline in the crankcase. The superabundance of Carbon Residue results from blow-by of partially burned gases of combustion which are heavy in free carbon content, and which transmit their free carbon directly to the crankcase oil. The unusual percentage of Ash is evidence that certain incombustible matter has found its way into the oil. The Nature of the Ash indicates that this incombustible matter consists of wear products from the piston rings and cylinder walls.

The Precipitation Number merely repeats the information already obtained above under Carbon Residue and Ash, but also includes the oxidized oil or asphalts. The difference between the two Precipitation Numbers listed is the per cent of asphalts or oxidized oil. The oxidized oil is a product of normal oil depreciation in service. The presence of the Iron Sulphate points to Sulphuric Acid as the cause of the Acid Reaction.

The Station's report on the oil described above reads in part as follows: "All of these conditions show excessive leakage of exhaust gases between pistons and cylinder walls and absorption of the products of combustion by the oil in the crankcase. The free sulphuric acid in the used oil came from exhaust gases leaking into the crankcase. The sulphur dioxide in these gases was absorbed by the water in the oil and became oxidized to sulphuric acid."

Some of the wrist pins from the engine in which this oil had been used were forwarded with the sample of used oil. These wrist pins showed clearly the etching effect of the sulphuric acid found in the sample of oil. All of the unsatisfactory elements noted in the used oil could be attributed without the slightest stretch of the imagination to faulty conditions in the engine or to the method of operation.

In replying to another complaint on the service rendered by contract oils in gasoline engines, the Experiment Station's comments were as follows: "It has been our experience that dilution in lubricating oil with gasoline fuel is not a measure of the quality of the oil. When excessive dilution of the lubricating oil occurs, either too low viscosity oil has been used, or operating conditions are poor."

As stated above, the selection of the proper viscosity oil for any particular engine is a matter for the judgment of the engineer concerned, who has an intimate knowledge of the condition of the engine and the circumstances of operation. Possibly the first estimate of the viscosity required may be incorrect; possibly the condition of wear in the engine is such that proper lubrication is no longer a problem of selection of oil viscosity but a problem of overhaul. The first estimate of lubricating oil viscosity for the engine must be supplemented by intelligent observation of the depreciation of the crankcase oil to determine what factors are influencing the oil unfavorably. For this purpose, it is highly desirable that the engineer have at his disposal a few simple tests for determining the changes taking place in the oil.

In order to satisfactorily follow these changes in the crankcase oil it will be necessary for an observer to be equipped to note, (1) the degree of change in viscosity between the new and the used oil, (2) the reaction of the used oil (acidity, if any), (3) the percentage of gasoline present, (4) the presence of salt water, and (5) the amount of free carbon.

The only completely satisfactory apparatus for determining the viscosity of a lubricating oil is the viscosimeter and any activity extensively employed in automotive lubrication should be equipped with such an instrument, however crude. Various other means for comparing viscosities may be devised by the exercise of ingenuity, but the viscosimeter remains the most useful and expeditious. The reaction or inorganic acidity of the oil need not be determined accurately. It is only necessary to be able to recognize the presence of inorganic acids to know that gases of combustion are blowing by the pistons. To accomplish this, heat to approximately 150 degrees F. about 50 cubic centimeters of the oil and 15 cubic

centimeters of distilled water. Shake thoroughly, then allow to cool and settle. Transfer about 5 cubic centimeters of the aqueous layer to a test tube by means of a pipette and add one drop of 1 per cent solution of methyl orange. No change in color indicates no acids present. The percentage of gasoline dilution can be determined by comparison of the viscosity of the new oil with that of the used oil on a gasoline dilution chart. The presence of water in the oil can be detected by warming a sample of the oil in a glass dish. If the sample sputters and pops at about 212 degrees F., water is present. A portion of the aqueous layer from the reaction test can be used to test for salt. Titrate a sample of this aqueous layer with silver nitrate (now supplied to naval vessels for boiler water tests). Precipitation of white silver chloride will denote the presence of salt. The free carbon, water and other foreign matter in the oil can be determined by dissolving 10 cubic centimeters of oil in 90 cubic centimeters of motor or aviation gasoline in each of two centrifuge tubes and centrifuging for three or four ten-minute periods to constant volume. Each cubic centimeter mark on the standard centrifuge tube will represent 10 per cent sediment by volume or a precipitation number of 1.00. Examination of this sediment will furnish an idea of the amount of free carbon present. When a reading of 20 per cent sediment (2 cubic centimeters on centrifuge tube) is obtained, it is time to change oil, regardless of other considerations.

The tests listed above, except that for viscosity and gasoline, can be conducted by most naval vessels with equipment now carried for other purposes. Gasoline dilution could be taken for granted in cases where the used oil is noticeably thinner than the new oil. However, a viscosimeter is a practical necessity if any degree of refinement whatever is to be obtained in basing engine adjustments on crankcase oil depreciation.

The writer believes that systematic observation of the changes taking place in the lubricating oil will result in more reliable engine operation and more accurate engine adjustment than can be obtained by any other means afloat. Less frequent overhauls and lower lubricating oil consumption are corollaries to this procedure.

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STUDIES ON SOLIDIFICATION AND CONTRACTION AND THEIR RELATION TO THE FORMATION OF HOT TEARS IN STEEL CASTINGS.*

By Charles W. Briggs† and Roy A. Gezelius.†

ABSTRACT.

The following studies, resulting from a compilation of data and expressions, consider the relation of solidification and contraction to the formation of hot tears. Casting solidification involving the principle of equal cooling throughout is undesirable. Such conditions should be replaced by the more natural method of directional solidification. Controlled directional solidification is successful only when certain principles of casting design are adopted. These principles stress the importance of feeding smaller sections through heavier ones and by studying mass effect by the use of inscribed circles. Metal contraction and hindered contraction resulting from mold resistance is responsible in the major part for the existence of hot-tear cracks in steel castings. Other important factors are cavities and the physical properties of the steel. There are two types of hot-tear cracks, (a) the internal hot tear that develops during the solidification of the casting, and (b) the external hot tear that develops after solidification is complete, but while the temperature is about 1300 degrees C. Intelligent application of certain principles in casting design is one of the most important of seven methods that may be adopted to obviate the danger of hot tears, or at least limit the hot tear formation.

1. There are many conflicting opinions on all phases of casting procedure and various remedies for all the numerous problems arising in the industry. These remedies often have been applied by rule of thumb or as experience has dictated their use. It is surprising to note how little experimental data are available on the actual physical processes which occur during the solidification and contraction of steel castings.

2. It is not possible to review as large a field as the entire casting process in one article and do justice to all of its phases. The authors have selected, therefore, only one of the important phases, that of solidification, contraction and the formation of hot tears, and have attempted to bring together the best of available data and to supplement them with the results of some experiments.

3. In the industry today there are so many definitions for the several terms that in order to clarify the discussion it has been found necessary to define certain of these terms.

DEFINITIONS.

Contraction, Shrinkage.

4. This is a phenomenon, occurring in most metals, whereby a decrease in temperature is accompanied by a decrease in volume. The change may be divided into three types, (1) the decrease in volume in the molten metal while cooling to the solidification point, (2) the decrease in volume while changing from the liquid to the solid state, and (3) the decrease in volume while cooling from the solidifying temperature to room temperature.

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† Division of Physical Metallurgy, U. S. Naval Research Laboratory, Bellevue, Anacostia, D. C.

Pipes.

5. Pipes are cavities in the solidified metal caused by contraction and are formed during the change from the liquid to the solid state.

Contraction Stresses.

6. Contraction stresses are produced by hindered contraction and/or non-uniform cooling resulting in a non-uniform change in the volume of the metal. Contraction may be hindered by the resistance of the mold or by resistance within the casting itself due to non-uniform solidification.

Hot Tears.

7. Hot tears, or contraction cracks, are cracks in the metal formed at elevated temperature by contraction stresses. The steel is subjected to stress in excess of the tensile strength corresponding to the prevailing temperature and, accordingly, cracks. The formation of these cracks may be aided by contraction cavities (pipes) which cause a concentration of stress.

Cold Cracks.

8. Cold cracks are the result of large inherent contraction stresses produced during cooling from the solidification temperature to room temperature. These cracks appear at comparatively low temperatures.

SOLIDIFICATION.

9. The process of the solidification of metals has been studied both from the theoretical and the practical point of view by many competent observers. We refer to H. M. Howe,[1]* A. L. Field,[2] A. McCance,[3] H. C. Dews,[4] T. M. Service,[5] C. H. Desch,[6] J. E. Fletcher[7] and others whose studies in solidification have formulated certain rather definite rules.

10. The solidification of steel poured into the mold begins with the formation of a crust. As the temperature drops the solidification proceeds and the crust extends inward until the entire cross-sectional area is solidified. This crust formation does not proceed uniformly all over the casting; at feeding and gating centers it proceeds more slowly.

11. Castings composed of thick and thin sections will solidify so that the thick portions are still in the semi-fluid or fluid state, while the thin parts of the casting are solidifying and may actually be accomplishing part of their solid contraction. Let us consider these three conditions, liquid, liquid plus solid, and solid, with respect to contraction.

12. The authors find that there are, apparently, no reliable published figures on the changes of the volume of liquid steel with change in temperature. However, from the information at hand it seems reasonable to assume that contraction takes place uniformly with the drop in temperature and that it is about 2 to 4 times greater per degree drop in temperature than solid contraction. Thus, in order to keep liquid contraction low, the steel should be run as cold as possible. Practically, this feature is not considered to be of importance as the supply of liquid metal usually is ample to provide for the amount of liquid contraction that might be obtained, regardless of the pouring temperature.

13. The freezing contraction is much more important and much more difficult to control. Experiments by Benedick[8] and the calculations by Honda[9] have shown that steel passing from the liquid phase to the solid phase contracts about 5.5 per cent in volume. The free solid contraction

* Reference numbers as shown herein correspond with numbers in the Bibliography at the end of the paper.

of steel, from the freezing point to room temperature, is about 6.6 per cent (linear contraction about 2.2 per cent). This type of contraction will be taken up more fully in the following pages.

14. T. M. Service[6] explains the amount of contraction in steel in the following manner: Solid steel weighs 490 pounds per cubic foot (density 7.85) at 1500 degrees C. (2732 degrees F.), while fluid steel weighs 437 pounds per cubic foot (density of 7.0). Therefore, in order to obtain one cubic foot of solid steel, 1.12 cubic feet of fluid steel is required, or a total shrinkage of 10.72 per cent.

15. It has already been considered that in the solidification of steel castings the solidification proceeds from the surface inward and as it proceeds the three types of contraction take place simultaneously. Thus, when the casting has completely solidified there will be a contraction cavity at that place which was last to solidify, unless certain measures are taken to prevent its formation.

16. Pipes usually are thought of as a result of shrinkage alone, although some authorities still contend that occluded gases are also to be considered. This theory was first propounded by Fletcher[7] as a result of his studies on ingot solidification. Other authors apparently do not consider the phenomenon of gas inclusion to be particularly important as a cause of pipes in steel castings.

17. The presence of pipes in castings may be considered in many ways. Heuvers[11] is of the opinion that pipes may be treated in three ways. First, the pipes may be ignored as, in his opinion, they do not affect the strength of the casting except insofar as they favor the formation of hot tears due to stress concentration at these points. Second, the pipes may be prevented by the insertion of metal chills at points of considerable cross-sectional area, or by the use of chill plates. Third, the design must be such that the foundryman can get to each section of the casting to feed it through direct feeding heads, or, at least, through sections of similar or larger cross-section.

18. These measures consist in casting in such a manner that the last solidifying portion will have an ample amount of metal to replace that lost during contraction. If the casting is not fed from some molten reservoir, a cavity will form in that portion of the casting that is last to solidify, or in any portion that is cut off from the supply of molten metal. In this case the volume of such cavities depends on (a) the mass of the metal solidifying, (b) the volume change of the metal, and (c) the casting temperature. Part (c) is really, for that matter, a portion of (b) because the extent to which casting temperature influences contraction is governed essentially by liquid contraction.

19. After a close analysis of the available literature on casting solidification, it is found that those who have expressed their ideas on the subject will generally end their discussion by pointing out that, if a casting could maintain an equal cooling rate and solidify uniformly throughout the casting there would be less defects from cracking of the casting. This could be done, they explain, by retarding the cooling of the thinner parts and by chilling the thicker parts to equalize the temperature of the casting.

20. It is true that if this can be accomplished, contraction stress arising from unequal cooling of sections would be eliminated. It is a nice picture, but it is fundamentally unsound for several reasons.

21. A casting with an equalized temperature throughout will proceed, upon reaching the solidification stage, to solidify from numerous points throughout. These points as nuclei for solidification will spread, and at those places where the solidified portions came together there will be small contraction cavities. It is true that there should be no large pipe or cavity but, instead,

there would be minute cavities throughout the casting and a general unsoundness would be the result. Nor does such a method insure against the formation of cracks, as other investigators as well as the authors show that pipes and cavities are of importance in the formation of hot tears.

22. The casting cools from the face of the mold inward, as the mold acts as an effective chill. How, then, can cooling of thinner parts be retarded so that an equal temperature throughout the casting may be obtained? Even though the thick portions of the casting were internally chilled to bring them to the temperature of the thinner portions, the casting still would not solidify equally throughout but a skin of a certain thickness would always precede the mass of the casting in solidifying. A high-frequency coil might be used to replace the radiated heat by induction, but this practice would add greatly to expense.

23. Solidification by uniform cooling must be discarded and what has been called *directional solidification* offered in its place. Directional solidification is a process that is intimately involved with the design of the casting. It makes use of the idea that there should be a reservoir of liquid metal adjacent to the solidifying portions of the casting. As the casting proceeds in solidifying, the last liquid portion is fed directly by a head so placed that it will provide the required liquid metal to compensate for the final solidifying contraction and thus promote complete metal soundness.

24. The outstanding principle in casting design, to obtain directional solidification, is to feed a smaller section through a heavier one. Of course, at times the design is such that this is impossible, and then the correct and intelligent use of chills may be resorted to in order that the heavier section will complete its solidification prior to the lighter section through which it must be fed. Directional solidification also necessitates the precaution that molds and cores should be made as collapsible as possible in order to reduce the stress arising from mold resistance.

25. A plan of solidification involving controlled directional feeding is especially adaptable as it employs the methods that are involved in the regular solidification of a steel casting. It does more—it does not permit sections to solidify heterogeneously throughout the casting, but controls the directions of solidification so that adequate reservoirs of liquid metal will feed the last solidifying portions.

26. The authors are of the opinion that in order to obtain castings free from pipes and voids it is necessary to have controlled directional solidification taking place within the casting.

Rate of Skin Formation.

27. A question that is ever prevalent when directional solidification is considered, and always asked by those interested in this method, is this: At what speed does directional solidification proceed? In other words, in a study of this nature the rate of skin formation is one of the important factors involved.

28. The rate of skin formation, based on our present information, depends on two conditions: First, the casting temperature, or perhaps better, the fluidity of the poured steel; and second, the rate at which heat can be conducted away from the mold-metal interface. Thus, the surface area and the concentration of mass of a casting would be influential in varying the degree of heat conductivity. In some sections a substantial skin is formed during the few seconds required for pouring the casting. In other larger sections where the concentration of mass is much greater, no skin at all will be formed during the pouring interval.

29. Constant volumes with varying surface areas will form, in a definite time interval, varying skin thicknesses. However, the change is not critical, for a 50 per cent greater surface area does not change the rate of skin formation. To demonstrate this fact, an experiment was performed using a 6-inch diameter sphere and a parallelepiped, with volume identical to that of the sphere.

30. The surface area of the parallelepiped was 50 per cent greater than that of the sphere. Each was gated with a 2-inch central downgate. The metal was poured into the casting through the central downgate, and after a predetermined lapse of time the mold was turned over and the liquid metal remaining was emptied through the pouring gate. The pouring temperatures for the entire experiment were between 1550 and 1500 degrees C. (2822 and 2732 degrees F.). The results obtained are shown in Table 1.

TABLE 1.—EFFECT OF CONSTANT VOLUME AND VARYING SURFACE AREA ON SKIN THICKNESS.

Time elapsed between filling mold and overturning mold, in minutes.	Linear thickness of solidified shell, in inches.	
	Sphere.	Parallelepiped.
0	0.18	0.18
½	0.31	0.32
1	0.56	0.55
2	0.75	0.75

31. Experiments involving the changing of surface area and the concentration of mass in regard to their effect on the rate of skin formation are being studied further by the authors. A study of temperature conditions and the rate of heat conductivity in the mold also is receiving attention. This is very important if the entire story on the rate of skin formation is to be known.

Fluidity Tests.

32. It has been mentioned that fluidity is a factor in the process of solidification. The difficulty is that, although it is recognized by all foundrymen as a dominant feature in casting technique, very little is known about controlling it. In fact, its control is one of the major problems in steelmaking today.

33. It has been known for some time that certain processes produce a more fluid steel at lower temperatures. We refer particularly to converter steel and point out that it is for this reason as much as any other that European foundries have maintained the converter practice. Just how much difference there is in the degree of fluidity of the best made open-hearth and electric, or acid and basic steels, is not definitely known. However it is evident that the fluidity of steel is not altogether a function of temperature.

34. Which is to be considered the more important, temperature or fluidity? We are inclined to believe that fluidity is of greater importance, since the primary consideration of every foundryman is to run the casting completely. Then, too, the greater the fluidity, the easier it is to control directional solidification because the sections are more easily fed. The greater the fluidity, the greater opportunity there is, as will be shown later on, to fill up hot tears with liquid steel.

35. On a recent visit by Captain Shane, U. S. N., to the steel foundries of Europe it was discovered that a fluidity test was being used, especially by the French foundrymen, as an indication of the correct tapping or pouring

conditions. These foundrymen claimed a fair correlation of conditions existed and that favorable results were obtained.

36. The use of a fluidity test instead of a stop-watch test seems to be the ideal way of obtaining advance knowledge of the mold-running ability. However, at the present time it appears that a definite correlation of conditions will be difficult to obtain; at least this has been the experience of the International Nickel Co. and the American Steel Foundries. At the Naval Research Laboratory, fluidity is being studied by using a modification of the Bureau of Standards horizontal spiral fluidity mold.[21] The present data would indicate that numerous tests must be made before quantitative correlations can be obtained.

CONTRACTION AND TEMPERATURE OF HOT TEAR FORMATION.

37. The casting of steel presents several difficulties which arise entirely from the design of the castings and the properties of the steel itself. The hot crack is one of the foundrymen's chief difficulties. Hot cracks and pipes are so closely associated with each other that it is difficult to differentiate between the two. It is the authors' opinion that many hot cracks are due in part to small pipes which serve as points of stress concentration and facilitate tearing in the weak steel.

38. Information concerning the critical temperature at which cracking takes place and the strength of the steel at that temperature has been lacking for sometime. Several investigations have recently been carried out to determine these facts, notably those by Körber and Schitzkowski.[12] A few other writers such as Heuvers,[11] Singer,[14] Bennick[14] and Osann[14] also have contributed opinions on this interesting subject. In order to clarify the present views it might be well to mention some of these experiments and opinions in more detail.

39. Körber and Schitzkowski,[12] in what is probably the most comprehensive work of this character published to date, have determined the total shrinkage of cast steel to be approximately 2.18 per cent and the critical cracking temperature to be about 1300 degrees C. (2372 degrees F.). The experiments carried out to determine these facts were made on three types of bars, in dry and green sand using both acid and basic open-hearth steel. The bars in question were (1) plain round bars, (2) bars with large flanges to hinder shrinkage, and (3) bars identical with those used in case (2) with the shrinkage hindered by the insertion of rigid iron bars in green-sand molds.

40. The amount of shrinkage was measured by the shrinkage meter developed by Wüst[15] for his researches on cast iron. The bars were cast horizontally and the temperature measured by a platinum thermocouple, the hot junction of which was inserted at the surface of contact of the bar and the gate. The compositions of the steels used were as follows:

	Basic Open-Hearth.	Acid Open-Hearth.
Carbon, per cent	0.15–0.39	0.28
Silicon, per cent	0.32–0.47	0.22–0.60
Manganese, per cent	0.49–0.80	0.26–0.69
Phosphorus, per cent	0.014–0.047	0.063–0.106
Sulphur, per cent	0.021–0.045	0.036–0.085

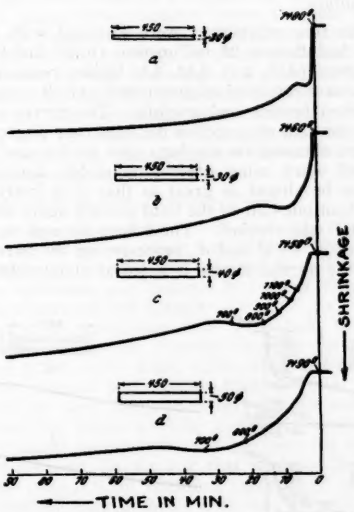

FIGURE 1.—SHRINKAGE CHARACTERISTICS OF PLAIN ROUND BARS. (ACCORDING TO KÖRBER AND SCHITZKOWSKI.) TEMPERATURES EXPRESSED IN DEGREES C.; MEASUREMENT OF BARS GIVEN IN MILLIMETERS.

41. As the experiments with acid and basic steels were carried on in identically the same manner and the results proved conclusively that the shrinkage characteristics of the two types of steel were the same, only one set of the experiments will be given in detail.

42. The fact that acid and basic open-hearth steel have the same shrinkage characteristics is particularly interesting, since various opinions have been presented as to which type of steel is more conducive to cracking. None of these opinions, however, have been substantiated by actual measurements under identical conditions, and therefore they have not carried a great deal of weight.

43. The procedure followed and the results obtained are summarized below:

A—Plain Round Bars.

44. The bars used were 450 millimeters (17.72 inches) long and 20 millimeters, 30 millimeters, 40 millimeters and 50 millimeters (0.787, 1.181, 1.575 and 1.969 inches, respectively) in diameter. These bars were all cast in green sand and measurements taken on shrinkage. The curves obtained are shown in Figure 1. The highest point on the curve represents the pearlite point. The total shrinkage was found to be independent of the diameter of the bars and was about 2.18 per cent. Approximately one-half of the total shrinkage occurred before the bars passed through the critical point.

B—Bars with Flanges.

45. The bars in this experiment were identical with those used above, except that they had flanges 20 millimeters (0.787 inch) thick and 12, 13, 14 and 14 millimeters (4.73, 5.11, 5.51, 5.51 inches, respectively) in diameter. The molds in this case consisted of green-sand and dry-sand molds composed of compo (chamotte) fireclay and graphite. The curves *a*, *b*, *c* and *d* (Figure 2) represent the data obtained on the bars cast in green sand, and *a'*, *b'* *c'* and *d'*, the data obtained on the bars cast in dry-sand molds. The total shrinkage obtained when using green-sand molds, approximately 2.07 per cent, was found to be almost as great as that of a freely contracting plain round bar, with about one-half of the total amount again occurring before the critical temperature was reached. These bars showed no defects.

46. In the curves *a'*, *b'*, *c'* and *d'*, representing the bars cast in dry sand, a deviation from the normal course is noted at about 1300 degrees C. (2372

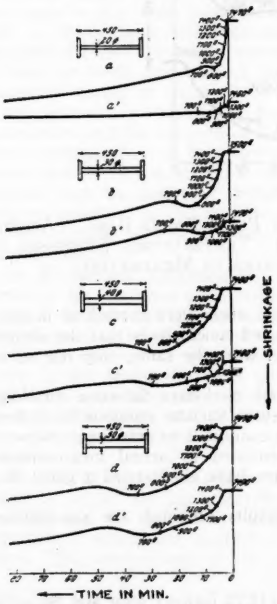

FIGURE 2 (LEFT).—SHRINKAGE CHARACTERISTICS OF BARS WITH FLANGES. (ACCORDING TO KÖRBER AND SCHITZKOWSKI.) TEMPERATURES EXPRESSED IN DEGREES C.; MEASUREMENT OF BARS GIVEN IN MILLIMETERS.

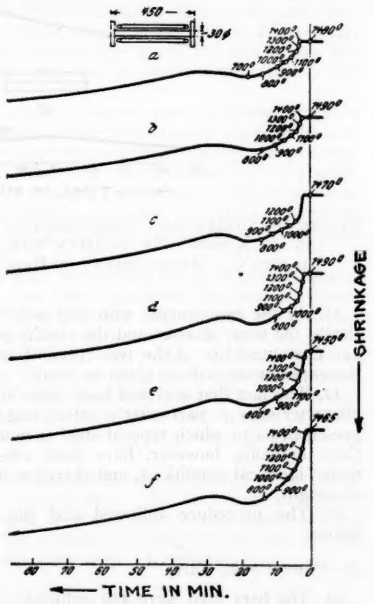

FIGURE 3 (RIGHT).—SHRINKAGE CHARACTERISTICS OF BAR WITH FLANGES AND RESTRAINING BARS IN THE MOLD. (ACCORDING TO KÖRBER AND SCHITZKOWSKI.) TEMPERATURES EXPRESSED IN DEGREES C.; MEASUREMENTS OF BAR GIVEN IN MILLIMETERS.

degrees F.). This deviation indicates a fracture in the bar; all of the bars fractured. The two larger bars fractured below the gate in the center of the bar, whereas both flanges were torn off the two smaller bars. None of these fractures showed any evidence of plastic deformation.

47. In this experiment the total shrinkage was found to increase with the increasing diameter of the bar and amounted to 0.34, 0.61, 0.89 and 1.78 per cent, respectively. The shrinkage before and after the critical point was 0.21, 0.18, 0.41, 0.89 per cent and 0.13, 0.41, 0.48, 0.89 per cent, respectively. In the two larger bars the shrinkage before and after the critical point is again approximately equal.

C—Bar with Flanges with Iron Rods in the Molds.

48. The experiment was conducted in green sand only and was intended to produce a mold the resistance of which was between that of a green-sand mold and a dry-sand mold. In this case only the 30-millimeter (1.181-inch) bar was used. The shrinkage was hindered by rods of 20 millimeters (0.787 inch) diameter placed between the flanges.

49. Various lengths of restraining rods were used to obtain different amounts of resistance. The total distances between the ends of the rods and the flange were 0.787, 0.157, 0.236, 0.315, 0.397 and 0.472 inch. In the two latter cases the distance was greater than the total shrinkage of the bar, 0.354 inch, but the sand compressed between the end of the rod and the flange diminished the actual working distance somewhat.

50. The total shrinkage varied from 1.51 per cent for the most hindered contraction to 2.10 per cent for the bar that was impeded the least. The contraction after the critical point remained constant in every case, whereas the contraction before the critical varied from 0.51 per cent to 1.04 per cent. All of the bars were torn near the flange. No defect was visible in the three bars which had been impeded the least until about 0.039 inch had been turned off, when small cracks were found, connected to a small pipe in the flange. The shrinkage curves (Figure 3) show deviations marking the fracturing points.

51. Although the work given above has presented the most complete data on the subject, and the conclusions as to the critical cracking temperature probably are very nearly correct, there are some portions of the technique that could be improved. The use of plain round bars with the gate in the center is not conducive to uniform cooling; that is, the cooling must proceed from the ends of the bar toward the gate. The ends of the bar thus pass through the critical range earlier than the center of the bar, and the shrinkage recorded is the summation of the expansion and contraction occurring throughout the entire bar. This would account for the "flattening" of the critical point, which should show as marked peaks on the curves. The temperatures recorded at the gate represent the hottest points and not the temperature of the bar as a whole.

52. In experiments 2 and 3, where the flanged bars are employed, similar difficulties are encountered. The thermocouple in this case does not indicate the "true" cracking temperature but some temperature slightly below it. This is brought out by the fact that the majority of cracks occurred at the flanges, which would indicate that the hotter and weaker metal was located there. The variation between the true temperature and that noted by the thermocouple at the center is not very great, due to the large amounts of heat given off at various points in the bar as these points pass through the critical range, which tends to equalize the temperature to a great extent.

53. The authors are at the present time conducting a series of experiments in an endeavor to continue the work of Körber and Schitzkowski and deter-

mine the tensile strength of steel at the high temperatures where cracking takes place. Although the data are at present incomplete and not sufficient to warrant a conclusive statement at this time, we are of the opinion that the temperatures given above are very nearly correct.

54. In order to correct the experimental errors mentioned above, the authors made a study of the cooling characteristics of several bars. Three platinum platinum-rhodium and six iron-chromel thermocouples were used in noting the temperature in various portions of the bar. The three platinum couples were placed as follows: (1) about one inch from the end of the bar, the end of the thermocouple extending to the center line of the bar; (2) at the center of the bar, below the gate; (3) about three inches from

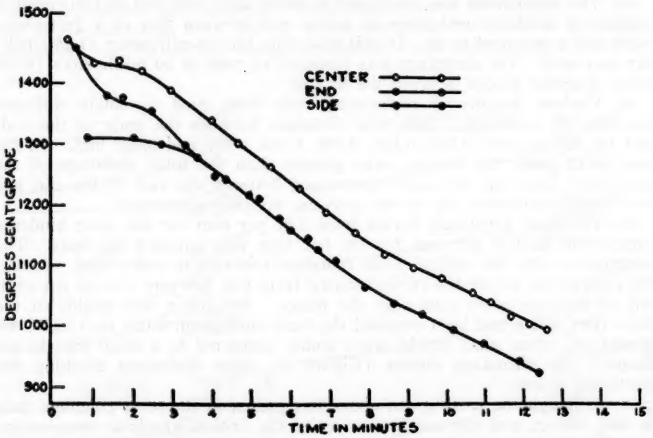

FIGURE 4.—COOLING CURVES OF A 2-INCH ROUND BAR.

the end of the bar, with the end of the thermocouple protruding only about one-eighth inch into the mold so that the temperature of the skin would be recorded.

55. In Figure 4 are shown the data obtained on a straight bar 2 inches in diameter. This bar was similar to that used by Körber and Schitzkowski in a portion of their work. It will be noted that the skin cools immediately to almost 1300 degrees C. (2372 degrees F.) and then cools very slowly. The fact that solidification proceeds from the end toward the center is shown very markedly by the fact that the temperature just below the gate lags about 75 degrees C. (135 degrees F.) behind that of the end and the skin in cooling.

56. To correct this, a bar has been selected having a diameter at the center slightly smaller than that at the ends. The thermal characteristics of this bar are shown in Figure 5. The thermocouples were placed in relative positions so that the data are comparable. It will be noted that the cooling is almost uniform throughout the bar.

57. Experiments to determine the maximum shrinkage and the critical cracking temperature of steel have also been conducted by Heuvers. His

results, which he presents with no explanation of the technique used, agree very well with those given above and show that one-half of the total shrinkage of 2 per cent occurs within the limits of 1450 and 900 degrees C. (2642 and 1652 degrees F.) within a very short time, and that below 900 degrees C.

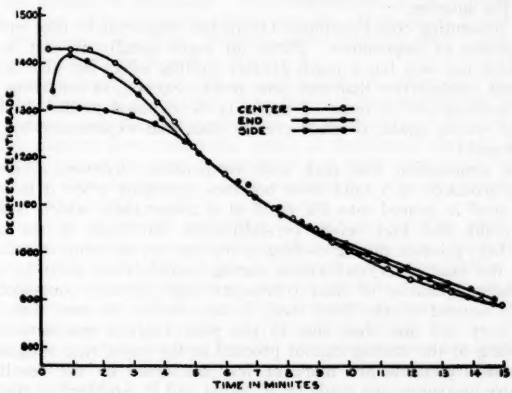

FIGURE 5.—COOLING CURVES OF A DOUBLE CONE-SHAPED BAR.

the additional shrinkage is very slow. He states further that "within the limits mentioned, *i. e.*, during the transition from the fluid to the pasty state and to the state of white-hot heat, the steel is rapidly subjected to great stress at a time when the tensile strength is still slight," and contends that these facts corroborate the work of Körber and Schitzkowski.

58. K. Singer[13,14] and Krieger,[14] who have also studied the problem, are of the opinion that the results presented by Körber and Schitzkowski are very nearly correct. The only published statement that differs considerably from those given above was presented by B. Ossan in a discussion of Heuvers' paper.[14] It is Ossan's opinion that the critical cracking temperature is very much below that given above. He believes that the true temperature is approximately 600 degrees C. (1112 degrees F.), and bases his argument upon the following points:

That it is impossible to determine the temperature of the cracked skin by means of a thermocouple placed in the mold.

"That a crack cannot occur as long as the steel is still in the fluid and, consequently, in a plastic state, because stress in this state causes deformation but no cracks. The plastic state does not cease until a temperature which is about 600 degrees C. (1112 degrees F.) is reached. Therefore, cracks can occur only when the steel has cooled off to that temperature, *i. e.*, when the skin has reached this temperature. However, the thermocouple introduced into the mold may still indicate 1300 degrees C. (2372 degrees F.)."

"That the cooling of the steel along the mold wall proceeds very rapidly due to the great temperature gradient. The critical temperature of 1300 degrees C. . . . will be reached in such a short time that it would be impossible to 'withdraw the mold.'"

59. Ossan continues that such wide temperature differences as he has mentioned, skin at 600 degrees C. (1112 degrees F.) while the center is still at or above 1300 degrees C. (2372 degrees F.), do exist. As an example he points out that ingots, whose external appearance is quite dark, begin to glow white hot when placed in the "soaking pit" due to the molten state of the interior.

60. In presenting this hypothesis Ossan has neglected to take into account several points of importance. First, an ingot usually is cast in a metal mold, which not only has a much greater chilling effect but also has a much higher heat conductivity than any sand mold. Second, in removing the ingot to the "soaking pit" it must of necessity be exposed to the chilling effect of the air, which, again, is much greater than that experienced by a casting in a sand mold.

61. The supposition that such wide temperature differences can exist in a casting produced in a sand mold becomes untenable when it is considered that the steel is poured into the mold at a temperature which is above the melting point, and that before crystallization can begin in the outermost crust the heat released during cooling of the steel to the point of solidification and also the heat of crystallization during solidification must be absorbed. As the latter quantity of heat represents approximately one-sixth of the total heat content of the fluid steel, it can readily be seen that the mold becomes very hot and that, due to the poor thermal conductivity of the sand, cooling of the casting cannot proceed at the rapid rate suggested.

62. These arguments are more or less confirmed by the results of the temperature measurements made by F. Wüst and P. Stuhlen[16] in their studies of temperature differences at different points of gray iron bars during the cooling process. They found that up to the pearlite point no temperature differences much over 100 degrees C. (212 degrees F.) occur between different points of the bar. This can also be seen by examining the curves shown above in the discussion of the work of Körber and Schitzkowski.

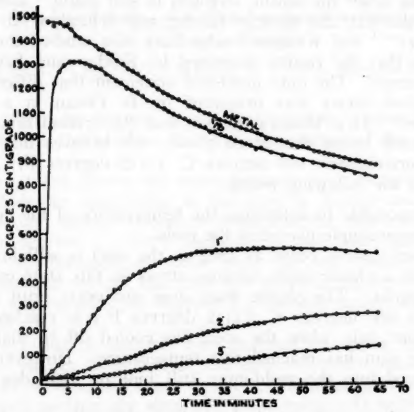

FIGURE 6.—TEMPERATURE CURVES SHOWING RELATION BETWEEN A 6-INCH CAST STEEL SPHERE AND SURROUNDING SAND; ⅛ INCH, 1 INCH, 2 INCHES AND 3 INCHES FROM THE CASTING SURFACE.

63. The authors, in an endeavor to determine how much of a temperature gradient existed in a sand mold, took temperature measurements on a mold in which a 6-inch diameter steel sphere was cast. The temperature of the metal at the center of the sphere was determined by means of a platinum platinum-rhodium thermocouple protected by a quartz tube, introduced through the bottom of the mold. The temperature of the sand was noted by means of four chromel-alumel thermocouples placed ⅛, 1, 2 and 3 inches from the mold-metal interface. Potentiometer readings were taken at short intervals and plotted, as shown in Figure 6.

64. By examining these curves it can readily be seen that the opinion presented by Ossan is untenable. The thermal conductivity of sand is so low that even though the temperature of the sand at the face of the casting is only 150 degrees lower than the metal at the center during almost the entire cooling range, the sand temperature one inch away from the casting never exceeds 1000 degrees C. (1832 degrees F.), and the sand two and three inches away is still lower in temperature.

65. The results of Körber and Schitzkowski may also be cited as proof that the cracking temperature chosen by Ossan is too low. In their experiments it was found that the cracking occurred where the highest temperatures prevailed, and that if shrinkage was not prevented until the temperature of this point in the bar had dropped to below 1000 degrees C. (1832 degrees F.), no cracks appeared. It has also been pointed out that in the region of 600 degrees C. (1112 degrees F.) and less, steel has such a high tenacity that cast steel bars in this temperature region break only after previous plastic deformation.

66. This is true even in the case of notch impact tests, which, because of the very nature of the stress, favor the formation of brittle fractures.[17] Therefore, if the cracks observed in the test bars at the transition to the flanges, or the gate, had occurred at the low temperature of 600 degrees C. (1112 degrees F.), preliminary plastic deformation might be expected.

67. No such plastic deformation was reported. On the contrary, it was found that the cracks always exhibited the characteristics of a fracture without plastic deformation. These fractures are explained by Körber and Schitzkowski by the assumption that slightly below the temperature at which solidification sets in, between the crystals which separate first and which form the first solid crust, small amounts of mother liquor melting at a lower temperature are still present.

68. K. Singer is another proponent of the higher cracking temperature. He, however, uses his theory of solidification, the refilling of cracks by molten metal, to explain why cracks are not more frequently found. His theory will be treated in detail in subsequent pages.

FACTORS EFFECTING THE FORMATION OF HOT TEARS.

69. Undoubtedly there are a number of factors effecting the formation of hot tears in steel castings. The foundryman's knowledge on this subject has been limited by the lack of fundamental research, and the result is that certain variables can be spoken of in only a qualitative way. It is very probable that some controlling factors which future work will stress more completely may be entirely missing from present discussions of this subject.

70. The factors that are at present deemed most important in the formation of hot tears are as follows:

(A) Contraction stresses—
  (1) Caused by mold resistance.
  (2) Caused by uncontrolled directional cooling.
(B) Pipes or cavities.
(C) The physical properties of the steel.
  (1) Strength at solidification temperatures.
  (2) Fluidity.

Contraction Stresses.

71. Mold resistance is very conducive to the formation of hot tears. It has already been pointed out in the review of the work of Körber and Schitzkowski that mold resistance can be sufficiently great as to fracture bars. It is hard to realize that rammed sand can exert such a resistance to the contraction of steel that fractures result.

72. The fact that some sands have a high compression strength and resist the contraction of the steel is not the entire story. The mold hardness and the amount of sand around the casting also are important.

73. Take, for example, the H-shaped section such as is often encountered in pulley wheels, gear blanks, valve bodies and the like. The sand between the two flanges restricts the casting from moving. It is true that the sand lying next to the casting loses its strength as it becomes burnt and that it will allow for movement of the two flanges toward each other, but the casting has little opportunity to avail itself of this small amount of play because the rest of the sand mold is rigidly shaped. Thus, it is not only a question of overcoming the compression strength of the sand between the flanges, but it is also a case of overcoming the resistance of the entire mold to the casting movement.

74. It is perhaps well known that green sand molds have less mold resistance than dry sand molds for the reason that dry sand molds will have a greater hardness and the sand a greater compression strength. Castings that crack in dry sand may not crack at all in green sand.

75. Cores are especially responsible for mold resistance. The core irons and reinforcing bars offer a resistance that is difficult to overcome. Later on in this article, methods will be considered whereby mold resistance can be materially decreased and in many cases eliminated.

76. The metal itself can set up contraction stresses of such a nature that cracking takes place. These stresses are the direct result of the manner in which the casting solidifies. The concentration of these stresses usually takes place at a rapid change in section of the casting where the thinner portion is solidified and the heavier portion partly fluid. The thinner portion would be contracting and the concentration of these stresses will be at the weakest point, which is the junction of the thin section with the thick section.

77. In many cases the stresses are concentrated by the solidifying metal and, as the mold resistance prevents contraction of the casting, hot tears are formed. It has been claimed that the concentration of these stresses is caused by uncontrolled directional solidification. If no thought has been given to the rates of solidification of various sections of the casting, the metal will solidify in such a heterogeneous manner that a thin section which has totally solidified will pull away from the thicker section which is in the critical range for crack formation.

Pipes or Cavities.

78. The authors consider that pipes and small cavities are factors in the formation of hot tears as they become centers of stress concentration. These

views are not held by everyone. K. Singer[13] is of the opinion that cracking is not associated with the formation of pipes and that the crack forms earlier than the pipe.

79. It is hard to believe that this statement tells the entire story about the formation of cracks. It is quite possible that cracks do occur while the casting is solidifying, but it is equally possible that cracking may occur after solidification is complete and while the casting is at high temperatures—for example, between 1300 degrees C. (2372 degrees F.) and the solidifying temperature.

80. Pipes and cavities form at the last point of solidification of a section, and thus are inherently the weakest points of the casting. It is well known that all types of cavities are points of stress centralization, and thus the two factors of metal weakness and stress concentration produce hot-tear cracks.

81. Theorizing is all very well, but are hot tears and cavities found to exist simultaneously in practice? The radiograph of Figure 7 and the photograph of Figure 8 show one of the numerous cases the authors have found in studying defective castings.

82. The radiograph (Figure 7) shows hot-tear cracks leading from a cavity. The photograph (Figure 8) shows another section of a casting that has been machined. It will be noticed that the cavity is in the center of a change of casting section where an abrupt change is made to a much thicker section. The cracks are clearly seen leading out of the cavity.

83. It has already been pointed out that abrupt changes in section are centers for stress centralization, and that if there is a lack of controlled directional cooling, pipes will form which become the point of stress application. The result is, as we see in the photograph, hot-tear cracks. The photographs also offer the suggestions that cracking takes place after solidification, or perhaps during the mushy stage of solidification, as otherwise the crack would not have been found penetrating the metal surrounding the cavity, since this portion of the crack would then have been filled by the last solidifying metal.

84. It frequently occurs that an external tear is indicative of the presence of an enclosed pipe or shrinkage cavity, particularly at the radiused junction of a flange with a body.

Physical Properties of the Steel.

85. The information that is available on the physical properties of steel at temperatures closely approaching the solidification temperature are nothing more than theories or suppositions resulting from an attempted interpretation of conditions that have been found by experience to exist. The greatest difficulty in this regard is that there are so many contradictory opinions that it must be admitted that our knowledge is very scanty.

86. It can be seen that the formation of hot tears depends somewhat on the physical properties of the metal. It is true that the strength at these high temperatures is quite low—so low, in fact, that a slight change may increase the strength by 50 per cent, 100 per cent, or more.

87. Then, again, how important is ductility at these temperatures? Is it not possible that the metal elongates under stress at these high temperatures, and, if so, would it be possible to increase the ductility? These are merely a few of the large number of questions that need answering.

88. On this question of physical properties for resisting cracking, there are two paramount and somewhat contradictory ideas in vogue. It is held by certain practical foundrymen that the higher the carbon (preferably 0.35-0.40 per cent), the greater the strength of the steel and therefore the

casting is more able to withstand hot-tear formation. Another group holds that the lower the carbon (preferably 0.20-0.25 per cent), the greater the ductility of the steel at the cracking temperature and the casting is then able to withstand hot-tear formation due to stretching or elongation.

89. Which of these views is correct, or are they both correct? Perhaps the carbon content is only indirectly responsible for the effects that are noticed. Carbon is not the only outstanding example of the use of alloying elements to resist cracking.

90. It is claimed that manganese adds strength to the metal at temperatures just below its solidifying range, and that nickel toughens the metal so that it will elongate instead of fracturing. Perhaps there are other elements that may be alloyed that would increase the strength or ductility more than carbon, nickel or manganese.

91. Then, too, it is well to point out that carbon, nickel, manganese or any other alloying element may have no appreciable effect at all on the strength or ductility of cast steel in the temperature regions just below the solidification range. These features are important and should be studied with the idea of obtaining quantitative information. Attention should also be called to the important role that oxygen and oxides may play in controlling the physical properties at these high temperatures.

92. For the sake of clarity it is pointed out that this discussion of alloying elements would apply only to solidified steel. It is rather difficult to understand how alloying elements could bequeath strength or ductility properties to steel in the mushy state of the solidification range. As cracks do exist at this stage, other plans for their elimination must be formulated.

93. The Naval Research Laboratory at present has set up a research of this nature and, although the problem is a tedious one, it is expected that in the near future information on the strength of steel as cast at high temperatures will become available.

94. Before leaving the subject of cracking in completely solidified steel, it should be pointed out that the temperature at which the hot tears take place will depend on the strength of the metal and the amount of stress on the casting. The strength of the metal increases very gradually from no strength at all just prior to solidification to what is still a very low figure at 1300 degrees C. (2372 degrees F.). Rosenhain[3] has claimed that mild steel of the type used in steel castings has, in the neighborhood of 1100 degrees C. (2012 degrees F.), a strength of a little over 2000 pounds per square inch, while in the neighborhood of 1300 degrees C. (2372 degrees F.) it is less than 800 pounds per square inch.

95. The amount of stress on the casting is that resulting from hindered contraction. Just prior to solidification of the casting the stress would be zero, and as the temperature drops the stress becomes greater. No data are available as to the comparable rates of increase in strength or stress due to restricted contraction at high temperatures. It has been observed, however, that in the neighborhood of 1300 degrees C. (2372 degree F.) the stresses developed by resisted contraction are sufficient to crack the casting. Below this temperature the strength of the steel increases more rapidly and is therefore sufficient to withstand the stresses that are developed by hindered contraction.

Fluidity.

96. French foundrymen have emphasized the importance of obtaining fluidity in cast steel, as in their opinion the smaller percentage of defects will be found in castings poured with a more fluid steel. There are points in favor of such a supposition. In the first place, the greater fluidity allows

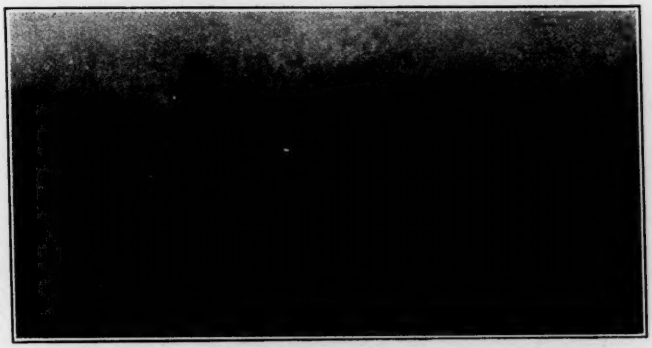

FIGURE 7.—GAMMA RAY RADIOGRAPH SHOWING PRESENCE OF A HOT TEAR EXTENDING FROM A CAVITY.

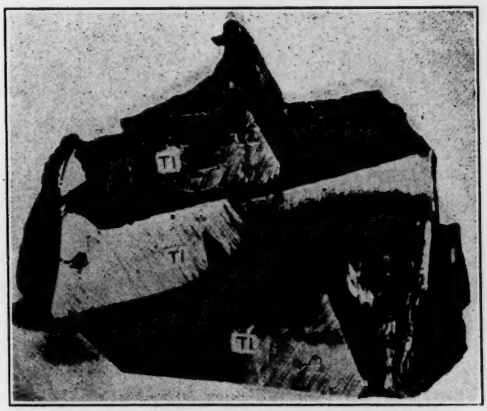

FIGURE 8.—HOT TEAR EXTENDING FROM A CAVITY IN CAST STEEL SECTION.

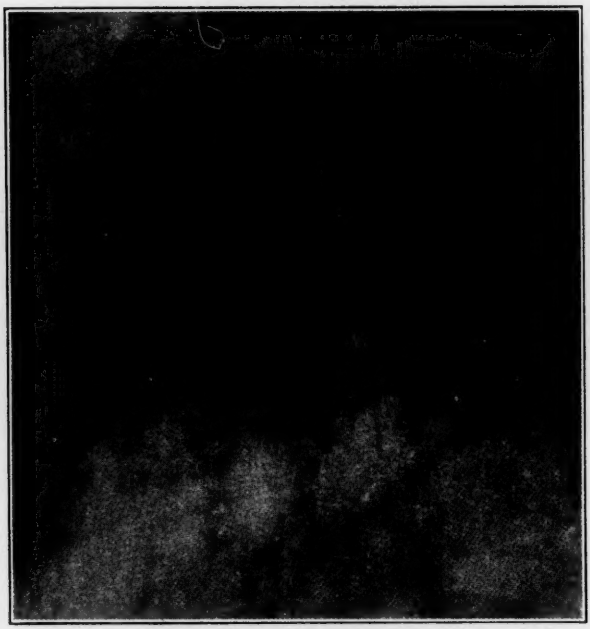

FIGURE 9.—GAMMA RAY RADIOGRAPH OF TYPICAL INTERNAL HOT TEAR.

FIGURE 10.—GAMMA RAY RADIOGRAPH OF INTERNAL HOT TEAR FORMATION.

for better controlled directional solidification and the possibility of filling up cracks. If a crack should form in a portion of the casting already solidified and the crack extends to liquid metal, then the greater the fluidity of the steel, the more opportunity there is for the crack to become completely filled.

97. It is quite possible that fluidity is the controlling factor rather than strength, and that the higher carbon steels (0.35 per cent) are not so susceptible to cracking. Singer makes the statement: "The higher carbon steels remain fluid in the mold for a longer time and pieces cast from these steels are, as we know, less liable to crack."

98. Singer stresses the fact that fluidity is responsible for non-cracking. However, he has forgotten that the cracking may take place after the casting has completely solidified but while it is still at a very high temperature. Fluidity certainly would have no influence on such conditions.

TYPES OF HOT-TEAR CRACKS.

99. In the preceding discussion the factors that are deemed most important in the formation, or in restricting the formation, of hot tears have been listed. It is now our plan to examine the methods of formation of hot tears. It is the authors' opinion that there are two types of hot tear cracks, as follows:

(a) The internal hot tear that develops during the solidification of the casting, and is caused by a lack of controlled directional solidification.

(b) The external hot tear that develops after solidification is complete, and is caused by stresses due to mold resistance. These cracks occur at temperatures slightly below the solidification temperature.

The Internal Hot Tear.

100. Internal hot tears are of a decidedly ragged nature with numerous branches. They have no definite line of continuity and usually exist in groups. These tears seldom terminate at the surface; in fact, most of them do not. When they do appear at the surface they are usually very small and difficult to locate. Upon exporing them downward they will be found to branch out and become more pronounced. The radiographs of Figures 9 and 10 show types of internal hot tears.

101. It has been said that the cause of the formation of these cracks can be traced directly to a lack of controlled directional solidification. It can readily be seen that the tearing is caused not only by the great differences of temperature in the casting, but that it also depends on the nature of the transition from the hottest to the coldest parts of the casting. A solidified section will pull away from a larger semi-solidified section if the transition between the sections is abrupt. However, if the transition is more gradual, the contraction forces are not so concentrated because solidification proceeds in a more controlled directional manner.

102. A lack of controlled directional solidification is also responsible for the lack of metal, and a cavity is the result. This cavity may form as a crack instead of a pipe in certain heavy sections, since the contraction of the metal toward the solidifying centers is sufficient to create a stress that tears the casting.

103. These tears occur and proceed from the inner solidifying face outward toward the surface, since the forces of contraction concentrated on the section will be sufficient to tear the weaker, less rigid portion of metal. Once the tear has started, it easily penetrates the stronger metal. This hypothesis can be correlated with the observed facts, as it is found that in the interior of the casting the tears are quite large, while they appear only as small cracks at the surface.

104. Encrustations and noticeable risings on the surface of castings have led to the opinion that crevices have formed in the steel casting which afterwards have been filled. Such encrustations of the surface have been found in castings at places where there is a danger of cracking, usually without any cracks in the surface being observed.

105. Singer and Bennek[18] have very logically explained these observed conditions. It is their opinion that as the walls of the mold were perfectly smooth at these places before the piece was cast, the encrustation must have arisen after the shaping of the casting, presumably because the solidified outer skin of the casting was ruptured at this place, a crack being also produced in the wall of the mold adjacent and adhering to this outer skin, in the same direction as the crack in the casting. The fluid steel making its way into the crevice soon after the rupturing of the outer skin also filled the crevice in the mold and thus led to the encrustation.

106. The filling up of cracks is a subject on which there is little information, although the idea is not a novel one. The principles involved are very similar to conditions of rock formation and the actions of intrusives, but certain favorable conditions must prevail.

107. In the first place, the crack must open up from the inner solidifying wall of the casting and proceed outward to the surface. The steel section must be thick enough to allow for gradual solidification toward the center of the section, and the steel must be of such a degree of fluidity that it will be able to flow through the crack to the surface of the casting. Of course, the actual distance through which it flows may be very short, as the skin of the casting may be only a few millimeters thick when the crack takes place. The difficulty becomes more pronounced as the solidification proceeds.

108. It is the authors' opinion that the filling up of cracks is the exceptional rather than the usual case, for two reasons. The contraction stresses are not usually sufficient to crack the skin at the first phase of solidification when the liquid metal does not have to proceed far to fill them, and the fluidity of the steel is so low that the liquid steel could not traverse the crack when the stress became sufficient to produce a hot tear. The latter statement is based on the typical American practice of pouring heavy castings at as low a temperature as possible.

109. To proceed with the supposition that cracks may be occasionally filled, it is suggested by Singer and Bennek that the cracks may be filled either by the general solidifying metal or by the mother liquor. In the first case the metal is forced into the crack under the pressure of the fluid column of the pouring gate, and the crack as filled will not differ in chemical composition from the material surrounding it. In the second case the impure, later-solidifying mother liquor is forced into the crack under the pressure of the contracting crust, and the crack in filling will have a higher carbon, phosphorus and sulphur content than the material adjacent to it.

110. Furthermore, they uphold their contention by exhibiting specimens of filled cracks which show segregations and, in places, a plainly visible transcrystallization of the filling metal in a direction perpendicular to the walls of the crack. If a crack can be filled with mother liquor in the manner described, then a filling with liquid reservoir metal is equally conceivable. It is rather difficult, however, to produce proof of this fact, since the material of the fractured outer skin and that filling up the crack usually shows no noteworthy differences in chemical composition.

111. The time at which the cracks occur in the first formed skin of a casting depends on the forces of contraction arising in the piece as it cools,

hence, on the form of the piece. If the form is such that cracks occur in the outer skin while it is still thin, then these cracks may have an opportunity to be filled from the liquid reservoir, providing the steel is fluid enough.

The External Hot Tear.

112. The external hot tear develops after solidification is complete but while the casting is at a temperature slightly below the solidification temperature, and it is caused by stresses due to mold resistance. The reason that the crack has been termed external hot tear, is that the crack first opens on the surface of the casting and proceeds inward. Such a crack has the appearance of a tear; that is, the face of the crack is ragged. The crack is wider at the surface and is uninterrupted in depth.

113. The cracking or the failure of such a casting would be comparable to the failure of a test specimen under load at a high temperature; the crack-

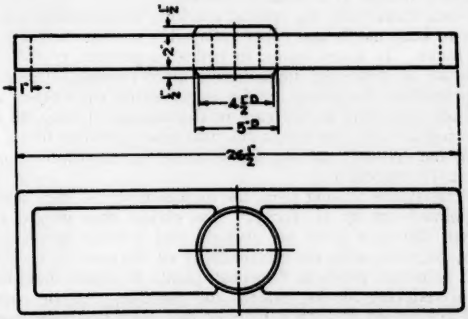

FIGURE 11.—PATTERN USED IN THE STUDY OF EXTERNAL HOT TEARS.

ing begins at surface irregularities which serve as points of stress concentration. It is obvious that mold resistance will depend upon the shape of the casting and the conditions of the molding sand. A mold that is collapsible in the danger zone can render the detrimental forces of contraction less effective.

114. In the study of external hot cracks, a pattern involving a hub and arm as shown in Figure 11 was molded in 3 ways, (1) in dry sand, (2) in green sand, and (3) in green sand made more collapsible by hollowing out that portion between the arms. The radiographs of Figure 12 show the amount of cracking as obtained by the variation of mold resistance. It will also be noticed that the cracks are wide at the surface and become smaller as they penetrate the metal.

115. The casting made in the collapsible mold shows no cracks at all. It may then be assumed that mold resistance caused the cracks, and that the greater the mold resistance, the larger the crack. There is little possibility that these cracks formed before solidification was complete, since there is no evidence of large internal tears.

MEASURES EMPLOYED TO OBVIATE HOT TEARS.

116. The formation and development of hot tears having been studied, it appears wise to consider methods that may be adopted to obviate the danger of hot tears, or at least to limit the tendency of hot-tear formation. In this regard the following measures are employed:

(a) Flexible molds and cores.
(b) The use of chills at the proper places.
(c) The application of ribs and wedges at certain changes of cross section.
(d) The use of a thermal non-conductive molding material.
(e) Casting in preheated molds.
(f) Pouring from elevated temperatures.
(g) Casting design.

(a) *Collapsible Molds and cores.*

117. It has been stated already that flexible molds and cores have a beneficial effect. Considerable time must be used in producing such molds, and the sand recovery after molding often is very difficult when cinders and the like are used in backing up parts of the mold and in the center of cores. The use of such molds, of course, is limited.

118. The data concerning the critical cracking temperatures show how important it is to keep molds and cores collapsible so that their resistance does not cause cracks. In many cases, in order to prevent cracking, the mold and cores must be destroyed immediately after casting. Immediate action is necessary because, according to the experiments of Körber and Schtzkowski and our own data in the case of thicknesses of from 20 to 50 millimeters, a period of only 2 to 4 minutes intervenes between filling the casting and reaching the critical cracking temperature in the neighborhood of 1300 degrees C. (2372 degrees F.).

119. Mold resistance arising from the negligent use of core irons has been repeatedly pointed out by G. Batty.[19] He claims that utmost care should be used to see that core irons are straight and pointed on the ends so that they will not interfere with the collapsibility of the core.

120. Great pains are taken in European plants to obtain mold collapsibility by the use of relieving blocks, cinders and the like. All tie rods and reinforcing bars are placed in such a manner that they protrude from the ends of the flask. This prevents the mold resistance that would arise from the sand compressing between the ends of the bars and the flask.

(b) *The Use of Chills.*

121. The use of chills is always a very uncertain measure and their presence is likely to cause cracks, the very thing that it is so desirable to eliminate. Theoretically, chills cool portions of the casting that otherwise would remain fluid longer than the surrounding portions through which the larger section is fed. If chills of the correct size are used, the process of directional solidification would be aided, with the result that the formation of hot tears would be unlikely. In other words, the chill acts as a method for reducing the dimensions of the piece, and the dimensions of the piece as well as the fluidity of the steel at the time of pouring determine how long contraction and solidification continue.

122. To overcome poor design—it is really only because of poor design that chills are used at all—is rather difficult. In the first place, the amount of cooling should be known, and the answer at best is only a guess. Thus, the mass of the chill is merely estimated. If the chill is estimated as a greater mass than is really required, then the section is over-chilled and contraction stresses are set up in a manner opposite to that which would have been experienced if no chill were used, with the possibility of the formation of a hot tear.

123. It has been observed that the use of too large a chill plate may crack a casting, due to a too-rapid development of shrinkage stresses. Like-

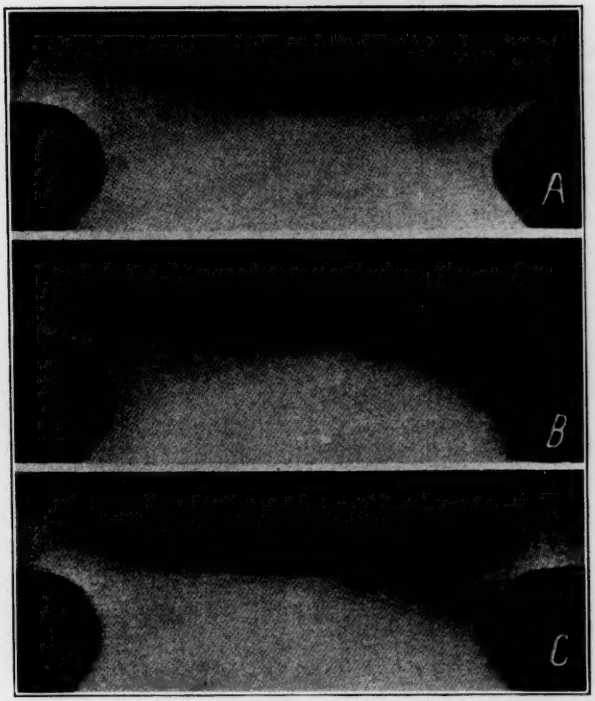

FIGURE 12.—EXTERNAL HOT TEARS AS OBTAINED BY VARIATION OF MOLD RESISTANCE. *A:* CASTING MADE IN DRY SAND. *B:* CASTING MADE IN GREEN SAND. *C:* CASTING PRODUCED IN COLLAPSIBLE GREEN SAND MOLD.

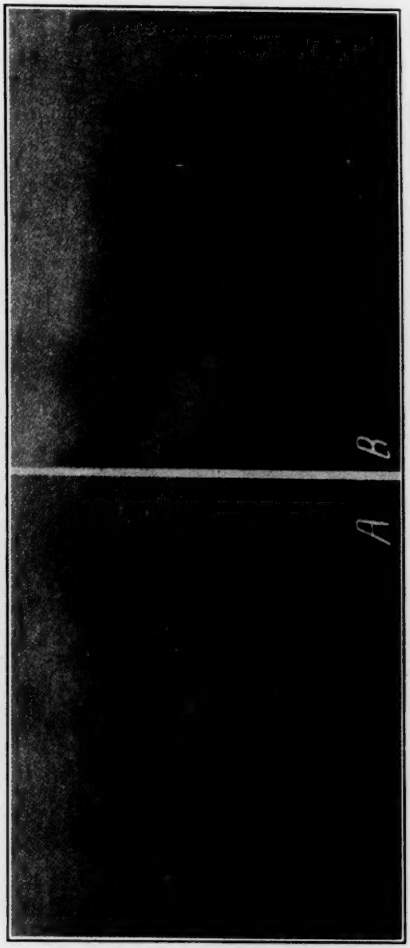

FIGURE 13.—GAMMA RAY RADIOGRAPHS SHOWING INFLUENCE OF INDIVIDUAL ADJOINING SECTIONS.

wise, a center of solidification is started which in many cases may not be desired. If the mass of the chill is less than that required, then solidification will not proceed as rapidly as is necessary to insure a sound section.

124. The discussion above has applied, in particular, to external chills. The use of internal chills is even more critical. If the mass of an internal chill is too large it will not fuse in, and along with the detrimental features just pointed out there will be the added one of lack of cohesion of the metal. Internal chills should be clean and dry, otherwise porosity is apt to result.

125. It is the authors' opinion that internal chills are more conducive to the formation of hot tears and other internal defects than they are to obviate these dangers. Their use is not scientifically controlled, and the dangers arising from their misuse are many.

126. Whatever can be accomplished by chills may be attained by the use of external chills with less danger of harmful results. It is true, of course, that the use of external chills involves more expense, since usually it is necessary to cast them in advance in order that they will fit the section which is to be chilled.

(c) *Application of Ribs (Brackets).*

127. The application of ribs has served to check hot-tear formations. They have been used rather extensively in this country with fairly good results. Their function is to solidify earlier than the sections which they adjoin, and in this manner act as a bond in preventing cracking.

128. Ribs do not eliminate the contraction stresses; they merely tend to prevent these stresses from centralizing at one point and rupturing the casting. The strength added to the surface skin by the presence of ribs acts to transfer coverging stresses over a wide area.

129. With some castings even a generous supply of ribs will be of no use; although the ribs themselves remain solid, cracks occur between them. In such cases the designer must come to the aid of the foundryman by providing for gradual transitions and smaller junctions between the sections of varying thickness.

130. The use of wedged-shape attachments to the casting on which gates and risers rest often are advisable, because all measures that are taken to prevent the formation of pipes in the casting will effectively lessen the danger of hot-tear formation. A disadvantage in the use of ribs and wedge-shaped attachments is their removal cost, which sometimes is considerable.

131. A few other points should be considered in the prevention of hot-tear formation. It has been previously shown that contraction stresses that arise suddenly within a casting are most conducive to hot-tear formation. In order to take steps to prevent these stresses from arising so suddenly, a slower rate of solidification must be effected. Even if this is not entirely possible, any step that can be taken in this direction must have a good effect.

132. Of course, the first suggestion is to increase the wall thickness of the casting, for the greater the section, the slower the cooling. However, in some cases this is not altogether desirable or feasible. The three other alternatives that are available are the use of thermal non-conductive molding material, casting in pre-heated molds, and pouring from elevated temperatures.

(d) *The Use of Thermal Non-Conductive Molding Material.*

133. It has been noticed that a skin forms quickly when molten steel is poured into a mold. The thickness or degree of formation of the skin depends largely upon the rate with which the mold material can conduct the heat away from the solidifying casting. Thus, the chilling action of the material of the mold has a great effect upon the rate of solidification of the steel.

134. If the mold material could be made less conductive of heat, the chilling action would be somewhat lessened. It is obvious that sand is much better in this regard than is a metal mold. A molding material that would have poor conducting properties must also have the good qualities that sand possesses, namely, adequate refractoriness and good moldability. These properties narrow the field perceptibly.

135. There remains magnesium oxide in one form or another, lime (plaster of Paris), asbestos and diatomaceous earth, and even these have various objectionable features. Asbestos and plaster of Paris lack good permeability, magnesium oxide and diatomaceous earth have little strength, and diatomaceous earth has such a high porosity that it would give trouble in casting because the air enclosed in the pores must escape in consequence of its expansion upon being heated. This air may attempt to escape through the steel, which would cause a porous casting.

136. It seems that, for one reason or another, these materials have limitations. However, they can be used in a mold, especially if they are used in combinations such as asbestos shreds and magnesium oxide or diatomaceous earth. A great moldability is thereby obtained and the heat conductivity considerably lowered. If these poor heat conductors are placed at the thin portions of the mold and the better conducting materials used at the thicker portions, a more even directional solidification may be obtained.

(e) *Casting in Preheated Molds.*

137. In regard to casting in preheated molds, it may be said that this is an excellent way to get around the excessive chilling action of the mold material. In a way, the same object is accomplished as in the use of thermal non-conducting materials, since the molten steel coming in contact with the warm walls of the mold does not cool so rapidly.

138. The preheating cannot be carried on at high temperatures, since the mold will crumble from lack of bond strength; then, too, the process is not favorably received because it causes difficulties in manufacturing schedules.

(f) *Pouring from Elevated Temperatures.*

139. Pouring from elevated temperatures as a means to avoid hot tears probably sounds like a foolish suggestion to most experienced steel foundrymen whose slogan for years has been "Pour her cold and prevent cracking." This opinion is urgently in need of correction. Steel poured hot will give excellent castings, and if it is a well-made, well-refined steel, thoroughly deoxidized, it will not have as great a tendency to the formation of hot tears as that which is poured cold. A great number of steel casting manufacturers do not make steel for castings but merely melt steel for casting; consequently, the formation of the slogan "Pour her cold."

140. It should be understood that the molds used in conjunction with pouring from elevated temperatures must be made of material which (a) will not readily be eroded by the high temperature metal, and (b) will not materially resist the progress of normal solid contraction of the casting. The gating and heading should be so devised as to insure good directional solidification.

141. Karl Singer,[18] one of the exponents of superheated steel, is of the opinion that the general idea that hot steel has a greater tendency to crack arose from the fact that the hot melts, which are richer in oxide, usually are not treated any differently from the colder melts and that the deoxidation of the steel bath therefore is not carried far enough. The result of this is that the hot melts are more often poured with a higher oxygen content. The FeO, which is already separating out at the time the hot cracks are formed,

lessens the slight tensile strength of the hot metal and thereby increases the danger of cracking. It is Singer's opinion that oxygen, or iron oxide, is a factor in formation of hot tears.

142. Regardless of the actual causes, the fact that steel poured hot produces satisfactory castings is established, and the reason for the greater tendency to hot-tear formation in castings made with hot steel cannot be attributed to the temperature. The pouring of a well-deoxidized steel from elevated temperatures, such as may be obtained from the electric furnace, will be found to be of advantage in casting thin-walled pieces with a tendency to crack.

143. If it is assumed that hot tears form during the transition of the steel from the plastic to the solid condition, then it can be shown that the temperature of the steel as poured is very important. For example, a high casting temperature will allow for a slow solidification of the casting, as the mold metal interface is superheated. Shrinkage stress will not arise suddenly, and a more uniform directional solidification can take place.

144. An advantage of low-temperature pouring is that a substantial elastic crust, capable of absorbing quite high tension stresses, forms while the mold is being filled. One of the disagreeable things arising from the use of low-temperature steel is the increasing proportion of entrapped gases. The thickly fluid steel should be limited to heavy sections. The principle of directional solidification should always be used.

145. Thin-walled sections that are liable to crack should be poured with superheated steel. Allowance must be made, of course, for the extra liquid contraction that takes place and for obtaining a well-made steel.

146. In summing up these points, it is the authors' opinion that the principal advantage of retarding solidification lies in the fact that an equalization of temperature takes place in the crust first solidified. By keeping the steel fluid in the mold for a longer time, directional solidification can be more readily controlled and suddenly applied stresses more easily eliminate.

(g) *Design.*

147. In a paper of this type the question of design should be given some attention. There is much to be said on so important a question, but to present a thorough study of it is not within the scope of this article.

148. There are as yet no definite rules of design which can be promulgated for every case, but it is possible to take specific cases and from them point out some generalities which might apply to similar designs. This has been done so frequently in the past that it is hardly necessary to mention more than a case or two until such a time as, we hope, more definite knowledge will be available to enable us to state what is the best design.

149. A study of proper design must include all of the factors mentioned previously in this article. It is scarcely to be expected that the most expert of designers will possess knowledge of the possibliities and limitations of foundry practice. Real cooperation should exist between the designer and foundryman in order that both may profit by the economies in time and money thus effected.

150. Statements of this kind have appeared so frequently in recent technical papers that they are no longer novel. In spite of this fact, no great steps toward cooperation have appeared. It may be true in isolated cases that a genuine endeavor is made to bring about an understanding between the foundryman and his customer, but such cases are rare and do not apply to the industry as a whole.

151. In most cases the foundryman never sees the pattern until it arrives at his plant to be molded. Then, even though he knows it should be modified,

he usually says nothing for fear he may lose the order or cast reflections upon his own ability. In many cases he would be money ahead if he did lose the order.

152. Most foundrymen will agree that a great many designs are unnecessarily difficult for foundry production. They are also agreed upon the fact that each casting is a problem in itself, and that foundry practice is an art and cannot be bound by definite rules or regulations.

153. The authors agree whole-heartedly with the first statement, but not entirely with the second. It is true that each casting as it is designated now is more or less a problem in itself. Even so, there are many general rules which apply to all castings and which every foundryman uses, subconsciously or otherwise.

154. However, there are at present no rules or limitations which apply to the designer. His main purpose is to design a casting that will perform the desired task with a minimum amount of weight and be at the same time pleasing to the eye. He has no knowledge of and as a rule is not concerned with the difficulties which may be met in production. He seldom realizes that in many cases he jeopardizes the entire casting for a small loss in weight or a slight gain in "beauty."

155. Accumulations of material are among the greatest dangers tending toward pipes and cracks. For constructive reasons it is not always possible to avoid them, but the designer can minimize the danger by providing gradual transitions from light to heavy sections.

156. Heuvers[11] has suggested a "simple and convenient method whereby the influence of individual cross-sections may be determined." This consists merely of inscribing circles within the cross-sections to be examined. The value of the method can readily be illustrated by examining the two radiographs (Figure 13) of ribs of two sizes joined to sections of an identical cross-section.

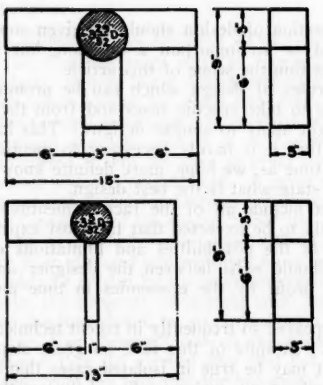

FIGURE 14 (LEFT).—INSCRIBED CIRCLES AS APPLIED TO ADJOINING SECTIONS.

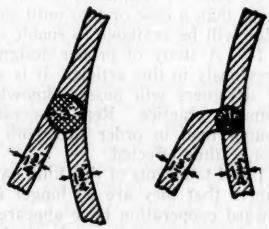

FIGURE 15 (RIGHT).—APPLICATION OF INSCRIBED CIRCLES AS AN AID TO DESIGN IN A RIB SECTION. (AFTER HEUVERS.)

157. In the diagram (Figure 14) these two sections are shown with the circles inscribed. It will be noted that the inscribed circles in each arm of the first T-section is 3 inches in diameter, whereas at the junction of the arms the diameter is 3-29/32 inches. In the second T-section the rib is but one inch thick and the inscribed circle has a diameter of 3-5/32 inches.

158. The radiograph of the larger cross section shows a flaw in the larger circle representing the accumulation of material. The second radiograph also shows a flaw, but one considerably smaller than the other.

159. Other instances where design could be improved are made clear by two further examples. The first, shown in Figure 15, is merely a section of a tube designed with a rib or foot such as frequently serves to support pipe sections. The design usually chosen is represented on the left. A design recommended by Heuvers and used to some extent in Europe attains the same purpose, and although it is less pleasing to the eye, is decidedly preferable from the standpoint of foundry technology. The accumulation of material in the design on the left, as shown by the areas of the inscribed circles, is 80 per cent greater than that of the more correct design.

160. The second example (Figure 16) is a portion of a commercially designed valve body. The right half of the cross-section shows the original

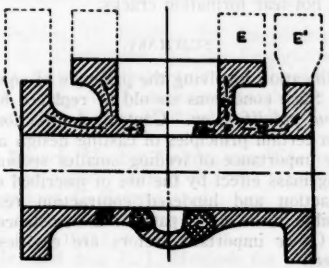

FIGURE 16.—DIRECTIONAL SOLIDIFICATION AS APPLIED TO A VALVE BODY.

design; the left half has been modified by the authors. The dotted lines indicate portions that are to be removed by machining, and the arrows indicate what the authors believe would be the direction of solidification.

161. The changes in section on the modified side are all gradual and tend to reduce the accumulation of material or to produce controlled directional solidification. Using Heuvers' method of inscribed circles to examine the casting, it will be noted that circle *A*, representing the average wall thickness, has a diameter of 1½ inches; and that circle *C*, representing the original design, has a diameter of 2½ inches, or an increase of 186 per cent in accumulated material.

162. By modifying the casting somewhat, a section as shown by circle *B* of 1¾ inches diameter may be obtained. This represents an increase in accumulated material of 36 per cent, which, although not perfect, is decidedly better than the original design.

163. The modifications on the flanges are similar to those pointed out by Wheeler[20] and, although they apparently cause an accumulation of material, simplify matters greatly by introducing controlled directional solidification. By examining the arrows on the original design it will be noted

that, as solidification will begin at the thinner sections, points D, D' and D'' will solidify first and solidification will proceed from these points. It then becomes apparent that, as far as feeding the hot point, F is concerned the heads E and E' are worthless. The head E cannot feed beyond the section D, the head E' beyond the section D', and the appearance of a cavity at F is highly probable unless other precautionary measures are taken to obtain directional solidification.

164. If the modified design is examined it will be seen that solidification is more or less controlled and will proceed toward the heads and thus maintain an open avenue for "feed metal" until the head itself has solidified. To obtain this end the head must be carried down the side of the flange, as otherwise the head itself might solidify before the heavy portion of the flange.

165. The studies on the formation of hot tears are in their infancy, and plans for a more complete research have been formulated. In the radiographic inspection of castings being purchased by the Navy, many conditions of external and internal hot tears have been observed. The fact that there are so many contradictory opinions regarding the nature and conditions of their formation has led the authors to express the above notes in the hopes that there will be greater cognizance of steel castings' most formidable defects, namely, the hot-tear formation cracks.

SUMMARY.

166. Casting solidification involving the principle of equal cooling throughout is undesirable. Such conditions should be replaced by the more natural method of *directional solidification*. Controlled directional solidification is successful only when certain principles of casting design are adopted. These principles stress the importance of feeding smaller sections through heavier ones and by studying mass effect by the use of inscribed circles.

167. Metal contraction and hindered contraction resulting from mold resistance is responsible in the major part for the existence of hot-tear cracks in steel castings. Other important factors are cavities and the physical properties of the steel.

168. There are two types of hot-tear cracks, (1) the internal hot tear that develops during the solidification of the casting, and (2) the external hot tear that develops after solidification is complete but while the temperature is about 1300 degrees C. (2372 degrees F.).

169. Intelligent application of certain principles in casting design is one of the most important of seven methods that may be adopted to obviate the danger of hot tears, or at least to limit the tendency of hot-tear formation.

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U. S. NAVAL CONSTRUCTION.

As a result of the opening of bids of July 26, 1933, when proposals were received in the Navy Department for the construction of 21 Naval vessels, Secretary of the Navy Swanson on August 3, 1933, awarded contracts to the lowest responsible bidder in each case, as follows:

Aircraft Carriers Nos. 5 and 6 to the Newport News Shipbuilding and Dry Dock Company, Newport News, Va., for the stated price of $19,000,000 each, subject to adjustments for changes in the cost of direct labor and material within certain definite limitations.

To the Bethlehem Shipbuilding Corporation, Quincy, Mass., Heavy Cruiser No. 40 for the fixed price of $11,720,000 without adjustment for changes in labor and material costs.

Heavy Cruiser No. 40 is the sixteenth 8-inch 10,000-ton Cruiser referred to in the London Treaty and under the express provision of that Treaty this vessel cannot be laid down before January 1, 1934, with a completion date for the vessel of January 2, 1937.

To the New York Shipbuilding Company, Camden, N. J., two Light Cruisers of the Nos. 42 to 45 Class, for the fixed price of $11,677,000 each, without adjustment for changes in labor and material costs.

To the Electric Boat Company, Groton, Conn., two Submarines, Nos. 174 and 175, for the fixed price of $2,770,000 each, without adjustment for increases in the cost of labor and material in accordance with the bidder's design. This price is on the basis of main propelling machinery being furnished by the Government and installed by the contractor.

Of the eight 1850-ton Destroyers, the contracts were all awarded on a fixed price basis without adjustment for changes in cost of labor and material as follows:

Bethlehem Shipbuilding Corporation, Ltd., Quincy, Mass., four Destroyers under the Act of August 29, 1916, for the fixed price of $3,896,000 each, and to the

New York Shipbuilding Company, Camden, N. J., four Destroyers to be built from funds allocated from the National Industrial Recovery Act for the fixed price of $3,775,000 each.

The six 1500-ton Destroyers were awarded as follows on the basis of a stated price subject to adjustments within certain definite limitations for changes in cost of labor and material:

The Bath Iron Works Corporation, Bath, Maine, two Destroyers for the sum of $3,429,000 each.

To the Federal Shipbuilding and Dry Dock Company, Kearny, N. J., two Destroyers for the sum of $3,410,800 each, and

To the United Dry Docks, Inc., New York, N. Y., two Destroyers for the sum of $3,400,000 each.

Owing to the fact that the working plans for the 1850 and the 1500-ton Destroyers will be furnished by the Bethlehem Shipbuilding Corporation and the United Dry Docks, Inc., respectively, the above prices for the other shipyards are subject to certain definite reductions for value of plans received.

The final allocations of vessels of the "National Industrial Recovery" program to Government yards was authorized today as follows:

Two Submarines to the Navy Yard, Portsmouth, N. H. (previously announced).

Two Destroyers to the Navy Yard, Boston, Mass. (previously announced).

One Light Cruiser and one Gunboat to the Navy Yard, New York, N. Y. (Gunboat previously announced).

One Light Cruiser and two Destroyers to the Navy Yard, Philadelphia, Pa.

Two Destroyers to the Navy Yard, Norfolk, Va.

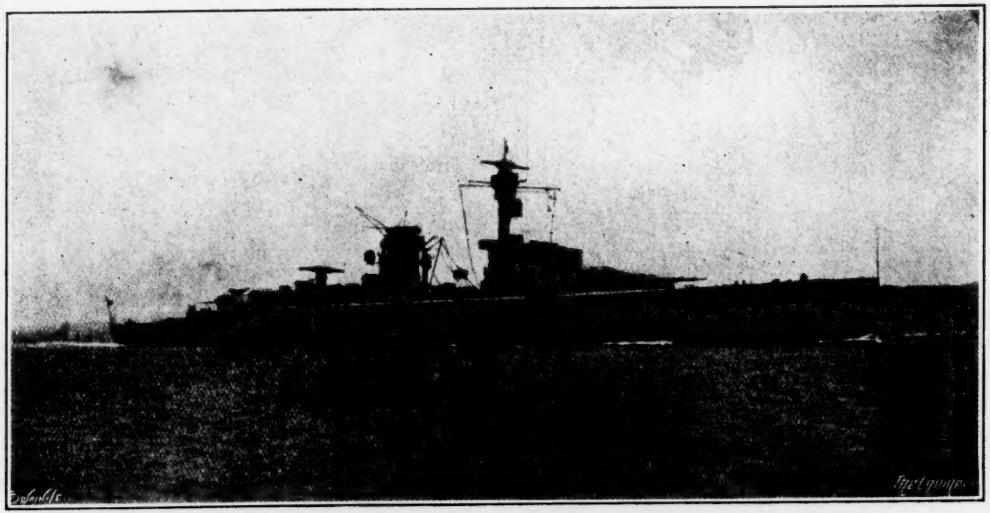
One Gunboat to the Navy Yard, Charleston, S. C. (previously announced).

Two Destroyers to the Navy Yard, Puget Sound, Wash.

Two Destroyers to the Navy Yard, Mare Island, Calif.

THE ARMOURED SHIP *DEUTSCHLAND*.

Commissioned on April 1st, the German warship *Deutschland* has now been in service for nearly three months. As the accompanying illustration shows, she is a smart-looking vessel. The upper works are so well proportioned that the triple 11-inch turrets fore and aft do not strike the incongruous note that might have been expected in view of the *Deutschland's*



THE ARMOURED SHIP "DEUTSCHLAND."

modest dimensions. Funnel and military foremast are not too obtrusive, and the general effect of the ship's profile is definitely pleasing. No excuse need be offered for thus dwelling upon her appearance, since most engineers, in common with sailors, regard symmetry as an element inseparable from efficiency.

Very little information, and none of official origin, has been disclosed about the *Deutschland's* trials, which lasted six months. This is not surprising, since Germany could hardly be expected to advertise to the world all the technical secrets of the most important addition she has made to her fleet since the war. At some future time, however, we may learn how the powerful Diesel plant, with a capacity of 56,800 B. H. P., acquitted itself during the sea trials. According to newspaper reports there was little vibration even at full power, though the noise is said to have been somewhat disconcerting. In the absence of fuel consumption statistics it is impossible to determine whether the remarkable endurance claimed for this ship—10,000 nautical miles at 20 knots—is actual or, as in the case of most steam-driven men-of-war, merely nominal. We should not be surprised to learn that the engines have proved entirely satisfactory, for it is hardly conceivable that Germany would have spent £3,750,000 on an experimental warship without having satisfied herself, by the most searching tests, that the experiment would prove successful. Further proof of her confidence is the fact that two further units of the class are under construction and a third is projected for next year.

From time to time such details of the *Deutschland* as became available have been quoted in our columns, including a full description of the propelling plant. It is therefore unnecessary to recapitulate all these particulars. Briefly, then, she is a vessel of 10,000 tons standard displaced, rated neither as battleship nor cruiser, but simply as an "armoured ship." This is undoubtedly the best designation, for although her armament pertains to that of a battleship and her speed to that of a cruiser, she is, in fact, neither the one nor the other. Had she been designed as a retort to the Washington 10,000-ton cruiser type, which is by no means certain, she could scarcely have been more effective. It may not be a pure coincidence that no further cruisers of this type have been laid down anywhere except in the United States since the main features of the *Deutschland* became known. Certainly it would be bad policy to go on building ships which are demonstrably inferior in fighting power to a new type of no greater tonnage. France, on her own admission, is so impressed by the German newcomer that she has deemed it necessary to maintain the balance by laying down a battle-cruiser more than two and a-half times the size of the *Deutschland*.

The last-named is 609 feet long overall, with a beam of 67½ feet and a draught of 21 feet 9 inches. The contract speed is 26 knots, and, as noted above, the cruising endurance at the relatively high speed of 20 knots is equivalent to a run from Hamburg to Hong Kong. Six 11-inch guns mounted in triple turrets, form the main armament. These weapons, it may be safely assumed, embody the highest ballistical properties consistent with their caliber, and they are probably equal to any gun afloat except the 16-inch and 15-inch. Incidentally, the British Admiralty's proposal to establish 11 inches as the maximum caliber for future capital ships is the best evidence that guns of this size are capable of fulfilling all the essential requirements of the naval artillerist.

No 10,000-ton cruiser now afloat could withstand a single well-aimed salvo from the *Deutschland*. The vitals of most of this class are notoriously exposed, and the effect of 11-inch H.E. shell on these huge, virtually unarmoured boxes of machinery would be devastating. It is true they could hit back with their 8-inch broadsides, but the German ship appears to be

well armoured over her sensitive parts, and there is little doubt that she could stand a great deal more punishment than her "egg-shell" opponents. The sole advantage possessed by the latter is their superior speed; but speed is not in itself a decisive tactical asset once serious battle has been joined.

To appreciate the far-reaching effects of the *Deutschland's* advent on naval construction, and naval policy in general, it is only necessary to envisage her in the *rôle* of commerce destroyer, and this may be done without lifting the argument out of the academic plane. How, then, could her depredations on the trade routes be countered? Six-inch gun cruisers would be useless save for observation purposes, and in heavy weather their superior speed might be so far neutralized that they would be caught and crushed by the 26-knot *Deutschland*. Nor would the 10,000-ton cruisers with 8-inch guns be in much better case. They could evade the enemy, but could they engage with any reasonable prospect of crippling him before they themselves were destroyed? A comparison of the armament and protection on each side provides a fairly conclusive answer to this question. There seems to be no denying the fact that the building of the *Deutschland* and her sisters has completely upset preconceived ideas of naval strategy, tactics, and ship design, and it remains to be seen what new principles will emerge from the momentary confusion.

It is a significant fact that this country is so fettered by Treaty restrictions that she would not be in a position to build ships capable of neutralizing the *Deutschland* even if the latter were a direct menace. We have, quite literally, surrendered the right of self-defence in the one sphere where adequate strength is indispensable to national existence.—"The Engineer," June 23, 1933.

THE LANGLEY FIELD CONFERENCE.

ALEXANDER KLEMIN.*

The National Advisory Committee for Aeronautics is a remarkable institution which the aviation industry is very fortunate to have. Its equipment is unequaled, and its financial resources are large. These resources, scientific and budgetary, are skilfully administered by a disinterested committee of scientists and an able director.

The Eighth Aircraft Engineering Research Conference, sponsored by the N.A.C.A., Langley Field, Va., May 4, 1933, was attended as usual by a representative group from the aviation industry and gave indication of much useful accomplishment. Certain definite directions in the research work stand out clearly. Perhaps the most important problem in the committee's program is that of lift-increase devices. Many such devices have, of recent years, originated with inventors, passed through various university laboratories, and have now been tested with greater thoroughness at Langley Field. The lift increases accomplished are truly remarkable, the record being held by the Fowler variable-area wing. In this device the rear under portion of the wing is made to slide back, while simultaneously, a specially designed Handley Page slot, consisting of an auxiliary airfoil at the leading edge, is put into operation. This combination of lift-increase elements resulted in a total lift increase of 285 per cent. It is true that a device of this character introduces mechanical complication, increase in structural weight, and additional expense in construction. On the other hand, such lift-increase devices, correctly applied, should really improve the low-speed characteristics of the

* Secretary, A.S.M.E. Aeronautic Division, and Professor of Aeronautical Engineering, Daniel Guggenheim School of Aeronautics, New York University, New York, N. Y.

airplane. The autogiro has received favorable popular notice by virtue of its ability to descend at a steep angle so that the landing speed is low and the roll on the ground short. If airplane constructors grasp boldly at this difficult means of increasing lift, they should eventually be able to approach the slow-speed characteristics of the autogiro without sacrificing the high speed of the airplane.

Closely allied with the problem of slow landing is the problem of lateral control. The difficulty of lateral control becomes greatest at high lift of the wing and slow speed of the airplane, yet it is precisely under such conditions that lateral control is most required. Recent investigations of the committee indicate that where a flap to increase lift is employed, an external aileron is almost essential, that is to say, one which is mounted some distance above the wing, and does not form part of the wing. Another method is to use a spoiler in which part of the wing is raised perpendicularly to the air stream to destroy lift on one side and therefore to produce a rolling moment. No system of lateral control is as yet perfectly satisfactory at low speed, and the committee is to be congratulated on its persistent efforts in the solution of this problem.

Perhaps the most striking novelty discussed at the Conference was the cyclogiro, a paddle-wheel rotary-airfoil system. Recently it was announced that Dr. Rohrbach had invented such a plane. An American inventor, H. H. Platt, has carried the cyclogiro idea so close to practicability that a very large wind-tunnel model of this devise is in process of construction. Theoretical investigation by members of the committee's staff indicate that a cyclogiro should be able to climb vertically with great velocity, hover, land vertically at zero forward speed, and at the same time have a quite respectable maximum top speed. It is possible that a successful direct-lift aircraft is just in the offing.

In the field of the power plant, perhaps the most noteworthy event of the conference was the announcement that a hydrogenated safety fuel developed by the Standard Oil Company of New Jersey, with a flash point of 125 F, gave the same horsepower and fuel-consumption characteristics as when the engine was operated on gasoline. In this fuel, therefore, there exists a valuable means of fire prevention on board an aircraft.—"Mechanical Engineering," July, 1933.

BRITISH AIRCRAFT.

On the basis of numerical strength, Great Britain, we believe, occupies fifth place among the world's aeronautical Powers. There are some who find that fact disquieting, who hold that as an island domain, no part of which is beyond the reach of hostile aircraft, this country ought to possess an aerial force at least equal in numbers to that of any possible enemy nation. Whether equality should be attained by increasing our squadrons and their equipment or by some measure of disarmament providing a general levelling down of the forces of all the Powers is, it is argued, a subject for the politicians to discuss. One way or the other, equality, it is urged, ought to be secured, and until it is achieved, so it is contended, we will remain exposed to aerial attack to an extent which almost invites it. When we recall the use made of the aerial weapon by our enemies during the war, and when we reflect on the great technical developments in the construction of aircraft and aerial munitions achieved since those days, we are bound to recognize that our present relative numerical weakness in the air has a definitely serious aspect. It is not, however, in any way a cause for alarm.

In aerial warfare, as in sea and land warfare, numbers undoubtedly count, but—and particularly so in the air—the ability to maintain the numbers is even more decisive. An initial superiority of, let us say, two to one, in the number of machines possessed might or might not be of critical importance. It would depend upon the nature of the machines, their concentration or dispersion at the outbreak of hostilities, and the tactical and strategic skill with which they were handled. Any advantage accruing from the initial numerical superiority would, however, very quickly vanish by reason of the inevitably rapid wastage which occurs in aerial warfare unless resources were available for maintaining the original superiority. In order to arrive at intelligent conclusions on this subject we must look, not only at the numerical strengths of our own and other aerial forces as they exist today, but also at the facilities which we and other countries possess for maintaining and expanding those forces in time of war.

On the *personnel* side of the question it is not within our sphere to write; the material aspect alone is our concern. We are satisfied that, on that score, this country is very favorably situated. Behind the Royal Air Force, with its limited number of squadrons, there is an aeronautical industry firmly established, highly organized, skilful and enterprising. There need be no fear whatever that if the call came our resources would fail to maintain the initial strength of our squadrons. It is certain that almost at a moment's notice a program of rapid expansion could be effectively undertaken. How strong is our position on the material side was fully demonstrated last Saturday at the Royal Air Force Display, and still more fully at the aircraft manufacturers' private show held at Hendon on Monday last. Some indication of the country's strength on a manufacturing basis is implied in the very holding of these two shows. At Saturday's display the performance of the latest types of machines with which the Royal Air Force is equipped was staged for all to see. At Monday's private show, not only the performance, but the constructional details of the machines were open to the closest inspection of guests invited from all the principal countries of the world. Secrecy implies weakness; in publicity there is strength. Doubtlessly some details of construction and performance were carefully guarded, but it is certainly true that facts were revealed which placed at the disposal of foreign representatives information of a kind likely to be valuable to them. The implication is obvious; in many respects our manufacturing position is so strong that we have little to lose by disclosing to others what we are doing. At first sight it might seem unwise to permit foreign experts to examine at their will the details of the "Heyford" express night bomber and to tell them quite openly that we are building fifteen machines of this design for the re-equipment of R.A.F. squadrons. Equally might the wisdom be questioned of exhibiting the modified "Fury" interceptor fighter and of revealing its speed—250 miles an hour. This machine is actually an experimental development of a type which is at present the standard equipment of our Home Defence Force. On the engine side one might wonder why we should exhibit and publish details of the two compression-ignition aero motors which have now passed their official tests—the Bristol "Phoenix" and the Rolls-Royce "Condor." The "Phoenix" is an air-cooled engine developing 350 H.P. at sea level and having a consumption of about 0.4 pounds of fuel per horsepower hour. Of the "Condor," which is still partly in the experimental stage, it is openly stated that its power is 480 to 500 H.P., that it weighs 1513 pounds and develops its maximum power at 1900 R.P.M. Machines fitted with these engines were exhibited and flown at Saturday's display, and on Monday a Horsley torpedo bomber with a "Condor" engine was shown to foreign and British guests alike.

As yet another illustration of the same apparently unwise publicity it may be recorded that in the most readily accessible corner of the "New Type Park" on Saturday there was exhibited a Fairey machine fitted with a Rolls-Royce "Kestrel" engine having special devices designed to hasten the coming of the silent aeroplane. It is true that a sentry with fixed bayonet stood guard at the entrance of the "park," but a public pathway was provided round it from which as good a view of the "silent" aeroplane and some others could be secured as was to be had by obtaining a pass to admit to the enclosure. We record these facts, not in any way in a spirit critical of the authorities, but because they seem to us very conclusive evidence of the strength of our position on the production side. The truth, the comforting truth, is, that long before any rival could make effective use of the information which may be revealed to him, we would have gone beyond the stage at which it was necessary or desirable to keep the information a closely guarded secret. Further evidence of the soundness of the British aeronautical industry and its ability to fulfil any demands which the Air Force might make upon it in time for war is provided by two additional facts demonstrated on Saturday and Monday. The first was the extent to which British machines and engines are used in foreign air services. The second was the wide range and multiplicity of types produced in this country. When a British manufacturer undertakes to supply a foreign nation with military machines he is directly helping his own country in two ways. He weakens the foreign nation by making it dependent for its aerial equipment on British resources and he strengthens our own productive organization. The range and number of types produced in British workshops is of significance because it implies that no aspect of aeronautics is being neglected and that no development in any specialized branch is likely to be made anywhere without some one or other of our manufacturers becoming aware of it and being prepared to equal or surpass it.

While full credit must be paid to the skill and enterprise of British aeronautical firms we must recognize that the satisfactory position on the manufacturing side which we have indicated could never have been attained without the wise and consistent policy which has been followed by the Air Ministry. In its youth that Ministry, profiting by the experience of other State Departments, avoided suppressing initiative on the part of the industry. It specifies its requirements in broad outline, but leaves the manufacturers to carry out the design. In that way it has been responsible for the establishment and maintenance of the industry on a healthy footing. There are now about three dozen first-class companies, each with its own design staff engaged on the production of aircraft in this country, and about six which produce areo-engines. It might have been contended at one time that economy would have been secured by the establishment of a central official designing department, served by a body of outside contractors charged simply with the duty of correctly executing the ideas of the official designers. It is fortunate for the country and a factor of great importance in assessing its real aerial strength that the policy actually adopted was the very reverse. The aeronautical industry is today firmly established on a broad basis which promotes independent initiative without sacrificing the benefits to be derived from co-operation. So long as it remains as it is we need not worry overmuch about the relative strength of our air forces, for we have the undoubted assurance that behind those forces supplying them with their present requirements and capable of maintaining that supply in time of war there is an organization unsurpassed for efficiency by that of any other country.—"The Engineer," June 30, 1933.

WORLD PETROLEUM CONGRESS.

The World Petroleum Congress organized by the Institution of Petroleum Technologists, which has been held in London during the past few days, has been notable for the wealth of expert knowledge which it brought together. Of particular interest, however, in view of the policy of the Government towards the production of oil from coal, was the paper read by Mr. K. Gordon, of Imperial Chemical Industries, in which he gave an account of the researches which have led to the decision to erect large-scale plant for the production of light motor spirit from coal. The constitution of coal renders its hydrogenation essentially different from the hydrogenation of crude petroleum, but by a suitable choice of conditions, good yields of light oil had been obtained from all the British coals which had been tried, with the exception of anthracite. Moreover, with the choice of suitable catalysts, the hydrogenation of the vaporized light oils could be arranged so that any type of petrol could be made. It is of interest to note that no fewer than 236 papers have been contributed to the Congress under three sections, *viz.*, geological, production and refining, hydrogenation being a subsection of this last section.—"Shipbuilding and Shipping Record," July 27, 1933.

HYDROGEN-PROMOTED COMBUSTION IN MARINE OIL ENGINES.

Recently there was erected in this country an Erren demonstration engine, fitted specially to run on hydrogen. The unit was originally a Krupp single-cylinder two-stroke crankcase scavenging Diesel motor with a diameter of 232 millimeters (9⅛ inches) and a stroke of 280 millimeters (11 inches), the rated output being 20 B.H.P. at 325 R.P.M. It was converted by removing the fuel injector and fitting an adjustable hydrogen inlet valve, and we are informed that the output was raised to 28.6 B.H.P. at 360 R.P.M., 32.5 B.H.P. at 400 R.P.M., and about 40 B.H.P. at 450 R.P.M.

The gas, in this particular case, is stored at a pressure of 130 kilograms per square centimeter (about 1850 pounds per square inch) in five cylinders, with a provision for connections to five more. A reducing valve lowers the pressure to between 1 kilogram and 3 kilograms per square centimeter, thus indicating the small proportionate quantity of gas consumed. The hydrogen is admitted after the bottom dead center, the engine having taken in a normal charge of air on the suction stroke. Although no brake was installed at the time of our inspection of the plant, by the invitation of Mr. Rudolph A. Erren, we were interested to see the unit running light. The exhaust was invisible and, of course, non-poisonous, consisting of water vapor and nitrogen. Electric ignition is employed.

We have dealt first with the hydrogen-air engine by way of introduction to the subject of the use of the gas, which has an extremely high rate of flame-propagation and is known to give almost complete combustion in the case of heavy oils. There are now to be considered two important points. One relates to the economical production of the gas and the other concerns its application to the marine Diesel engine.

Water, split into hydrogen and oxygen by an electrolyzer, forms the basis of the proposition. Current for the electrolyzer is supplied by the main (or an auxiliary) engine driving a dynamo. The approximately complete combustion obtained by the hydrogen charge (the ordinary air suction charge remaining as in normal practice) enables the fuel supply to be reduced, it is claimed, by a surprisingly large amount. The electrolytic

process occurs at a pressure built up to a high figure; there is a standard type, with a current consumption of 4.2 Kw. per hour per cubic meter of hydrogen and 0.5 cubic meter of oxygen at 15 degrees C.

In land installations the oxygen would be considered a saleable article, to be separated and stored in high-pressure bottles. For marine work the promoting charge, in conjunction with the reduced fuel injection, would be both oxygen and hydrogen, and it is one of the characteristics of the Erren system that electric firing is adopted. The compression temperature is not a primary factor; the pressure of compression and the maximum firing pressures are reduced, but the mean pressure is increased.

It will be, not doubt, useful to consider an estimate based on certain electrical and chemical conditions. We will take a round figure of 100 B.H.P. hours with, say, a generous allowance of 45 pounds of fuel per hour; it is calculated that 11.26 B.H.P. per hour, equivalent to 8.4 Kw. per hour, will be required to generate two cubic meters of hydrogen and one cubic meter of oxygen. Used as a fuel, 2 cubic meters of hydrogen give 3.33 B.H.P. per hour, so that the oil is required to produce 111.26 B.H.P. per hour minus 3.33 B.H.P., or about 108 B.H.P. per hour.

The oxy-hydrogen charge would, it is assumed, give an increased output of 25 per cent., at the very least, bringing the figure of 100 B.H.P. to 125 B.H.P., whereas 108 B.H.P. represents the total required, *i. e.*, 38.8 pounds of fuel. This gives a saving of 6.2 pounds per 100 B.H.P. While, in certain circumstances, it is not our practice to dwell on estimates, the foregoing figures are not without their value and point to a source of power hitherto unconsidered in marine Diesel engineering. There has to be borne in mind the cost of the electrolyzer, the price of the mechanical conversion arrangements (reducing the compression pressure, adding electric ignition and providing an extra cam so that the starting air valve could act also as an oxy-hydrogen charge admission valve), together with the installation of gas containers and piping, their upkeep, etc. On the other hand, due to the more efficient and rapid combustion, the engine should, no doubt, operate under cleaner conditions than with a normal system of operation, while the lubricating oil consumption should be lower and the unit smaller for a given power.

Brake tests, fuel consumption trials and indicator diagrams, with and without the application of the oxy-hydrogen charging system to a Diesel engine are yet to be presented and we have no doubt it will be considered desirable to compile these results at an early date. Meanwhile, we are aware that much has been accomplished by way of preliminaries.—"Motor Ship," June, 1933.

MACHINERY FAILURES.

In the annual report just published by the British Engine Boiler and Electrical Insurance Company, Limited, proportionately more space is devoted to the various technical studies in which the company is engaged, than was the practice in the past. In part, this new departure may be regarded as the natural outcome of an increasing faith in the value of laboratory research, but, admitting this, the ultimate test against which there is no appeal is that of experience in actual service. Unless checked, thus, laboratory tests and office computations may prove seriously in error. In fact, where service conditions are relatively easy as in railway bridge work, it is notorious that some designers ignore the experience of the maintenance men, in a way which could rapidly bankrupt engine builders and machinery makers. It was considerations of this kind which enhanced the

interest and importance of the reports written by Mr. Michael Longridge, who had both the insight to see what was instructive in machinery failures and the capacity to describe these clearly and yet consisely. Many of the accidents on which he reported, occurred to engines dating from quite early times. The number of such engines is necessarily steadily diminishing, and in view of the higher standard of technical knowledge and the better quality of the materials now available, fewer accidents might be expected. Conditions are, however, undergoing a continuous change. Speeds have gone up to rates, which to an earlier generation, would have seemed incredible, the introduction of the internal combustion engine, and of the electric generator, and motor, brought in new problems to which must be added those peculiar to the steam turbine.

It is of interest to note that not a single accident to steam turbines is recorded in the report under review, though rumors have been rife of not a little trouble from disc vibration even in large units built by first-class makers. In all pioneering work, accidents are practically unavoidable, but unless these result in loss of life, it is to the insurance companies alone that the profession can look for impartial and instructive particulars.

The report under review is the first to be issued since the company responsible for its publication absorbed the historic Manchester Steam Users' Association. This was founded by Fairbairn in 1854 and made most important and valuable contributions to the improvement of engines and boilers. Amongst the most notable of its achievements was the demonstration of the baselessness of a one-time popular theory of boiler explosions. It was, in fact, contended that these were often not due to faulty design or to bad materials, but to phenomena, associated with the spheroidal state assumed by a drop of water in contact with a highly heated plate. Such a drop is supported on a cushion of steam, and so long as this cushion persists the transfer of heat is small and the evaporation low. As the plate cools, however, a point is ultimately reached, in which actual contact is established between the liquid and the hot surface, and the drop is then dissipated almost instantaneously into steam. It was held, and Tyndall seems to have accepted the view, that if boiler plates got overheated, and the feed were then turned on, a spheroidal state would be established at the outset, and that when this ultimately disappeared, steam would be generated in quantities to which no practicable safety valve could give relief and an explosion would be inevitable. This theory had the obvious advantage of largely relieving boiler makers from responsibility for defective designs or materials, and it was correspondingly popular. The Manchester Steam Users Association determined, however, to submit this attractive hypothesis to actual test. Under the direction of Mr. Lavington E. Fletcher, then chief engineer, a full-sized boiler was accordingly constructed in line with the best practice of the day, and was erected in a bomb proof shelter. The plates were overheated more than could ever be possible in practice, and the cold feed was then turned on. Nothing happened, and when the observers emerged from their safety retreats, they found the boiler intact. This particular experiment was, it should be added, only one item of an exhaustive series in which every detail of boiler construction and equipment was submitted to proof. Boiler practice was thus greatly improved.

Mr. Fletcher was succeeded as chief engineer by Mr. C. E. Stromeyer, who carried on the good traditions. The most important problem studied by him was that of water hammer, which was responsible for many fractures of steam pipes and valves. The precautions by which this danger has been eliminated are largely due to Mr. Stromeyer.

It is of interest to note that the Mr. Longridge, who founded the British Engine Boiler and Electrical Insurance Company, Limited, was at one time

chief inspector of the Manchester Steam Users' Association. To the report under review, the present editor, Mr. L. W. Schuster, M.A., contributes a valuable and instructive essay on the rationalization of bend tests. He establishes an approximate correlation between the reduction of area observed in tensile tests and the behavior of the material in bend tests. Hitherto, no definite relationship has been noted between the width and the thickness of a specimen, and its liability to crack when bent. Experience shows that the narower the bar, the greater is the angle through which it can be bent without the appearance of a crack. This is due to the fact with narrow bars, the metal flows freely. There is, however, a limit to the thickness of a bar which can be bent without distortion. In the case of mild steel this limit is about 0.81 times the thickness. Narrow bars crack at the edges, but bars having a width of five times the thickness, crack at the middle, and cannot be bent through as great an angle.

In a bend through 180 degrees, a wide bar, Mr. Schuster concludes, will be as severely tested as a square bar, if the former over which it is bent is 3½ times as much in diameter as that used in bending the square bar. The difference in the behavior of wide and narrow bars is traced by Mr. Schuster to the fact that with wide bars, lateral contraction is largely suppressed, and the flow of the metal is correspondingly retricted. With narrow bars the flow is free, and in some progressive bend tests of narrow bars made by him, the final length of some of the fibers was three times the original length. Of course, even greater elongations are noted in wire drawing, where lateral contraction is promoted instead of restricted, but after a certain number of passes, the metal has to be annealed, where as there was no annealing in Mr. Schuster's bend tests.

The facts to which Mr. Schuster calls attention are obviously important in the bend tests of fusion welds. In butt welds, for example, the weld metal cannot flow freely, either in a tensile test or in a bend test, and in the former case the reduction of area observed is not really characteristic of the weld metal. In another part of his report, Mr. Schuster describes a method of obtaining specimens of weld metal deposited in conditions approximating to those of actual use, and large enough for the production of satisfactory tensile test bars.

That cracked shafts may run for years before renewal becomes necessary has long been recognized, and further instances are recorded by Mr. Schuster. In one case, a cracked crankshaft had a useful life of five years. Another cracked crankshaft ran for eighteen months after the crack was first detected. The important point is to note the progress of the crack, and to condemn the shaft at once when the crack begins to take a transverse direction. Cracks often start at sulphide inclusions, taking the form of threads near the surface. One failure is reported in which a flaw having been found in a crank cheek, the makers had carefully concealed the defect by inserting a plug so neatly that its presence was not detected until the failure occurred. In a number of accidents discussed, the material of the faulty parts or components was found to be of objectionable chemical constitution or damaged by injudicious heat treatment. Nevertheless, indifferent material may, the report points out, give excellent service in conditions where it is not highly tried. In one instance, a crankpin with marked sulphide inclusions ran for forty years before failure, although the working stress was as much as 9 tons per square inch. One failure is reported in which no fault could be found with the material and not much with the design. This was the shaft of a rolling mill engine having a normal diameter of 18 inches but swelled up somewhat too abruptly to 25½ inches at the flywheel seat. Some twelve months before the shaft had to be condemned, cracks were

noticed at the change of section. These were cut out with a chisel and the engine allowed to continue at work. The remedy, however, proved ineffective, and the shaft had to be replaced. The main cause of the failure was the severity of the service.

Some failures are reported of shafts having oil holes drilled in them. The experience of the company is that such holes are not necessarily fatal, but where used, the factor of safety should be increased. A journal is, however, much more likely to fail at a fillet than at an oil hole.

That heat treatment of steel has its dangers, as well as its advantages, is shown anew by the failure of a splined shaft of nickel chromium steel. This had been hardened and tempered, but the stress thus set up led to internal rupture.

The insurance companies are at times accused of being unduly conservative in their attitude to fusion welding. The process is undoubtedly a most valuable one, but as in previous reports, several failures of badly-executed welds are recorded. One interesting case is reported of a failure directly due to compliance with the Board of Trade regulation that welded seams, subject to tension, must be reinforced by a riveted butt strap.

An unexplained explosion is reported of an autoclave used in the manufacture of beta amino anthraquinone by a secret process. The designed working pressure of the autoclave was 700 pounds per square inch, and before delivery it had been tested by its makers to 2000 pounds per square inch. Some three months before the accident it had again been tested hydraulically, the pressure applied being 1000 pounds per square inch. Nevertheless it exploded one morning, the cover being driven through the roof of the shop and flung on to a railway 332 feet away. It is admitted that the process of manufacture involved the use in the autoclave of a dangerous element, but the chemists concerned maintain that they have definite proof that this was not responsible for the accident. On the other hand, the careful study made by the insurance company after the explosion, showed very conclusively that, in some way or other, the pressure inside the autoclave must have become excessive.—"Engineering," July 21, 1933.

BOOK REVIEW.

STEAM, AIR AND GAS POWER, by WILLIAM H. SEVERNS AND HOWARD E. DEGLER. SECOND EDITION. PUBLISHED BY JOHN WILEY AND SONS, INC. LIST PRICE, $4.00.

The first edition has been modified and additional information added to bring the publication up to date. These additional data (as outlined in the Preface to the Second Edition) contain the Steam Tables of the American Society of Mechanical Engineers, descriptions and illustrations of recent power plant equipment, a short discussion of valve diagrams under the chapter on Valves, and a new and larger number of problems for classroom work.

The space allocation to main engines, boilers, auxiliaries, etc., remains approximately the same as in the first edition of the book.

The authors in issuing this second edition have apparently realized the importance of keeping those books, issued primarily for text purposes, up to date with the rapid changes in engineering practices and development.

A review of the first edition of the book can be found in the May 1929 edition of the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS.

LEON J. MANEES.

ASSOCIATION NOTES.

The following have joined the Society since the publication of the last preceding JOURNAL:

CIVIL.

Canfield, R. H., 2006 O St., N. W., Washington, D. C.

Dyer, W. E. S., York Road, Jenkinstown, Pa.

Frankel, Gilbert, 403 Commercial National Bank Building, Washington, D. C.

ASSOCIATE.

Adachi, S., Engineer Lieut. Commander, I.J.N.

Sakurai, T., Engineer Captain, I.J.N.